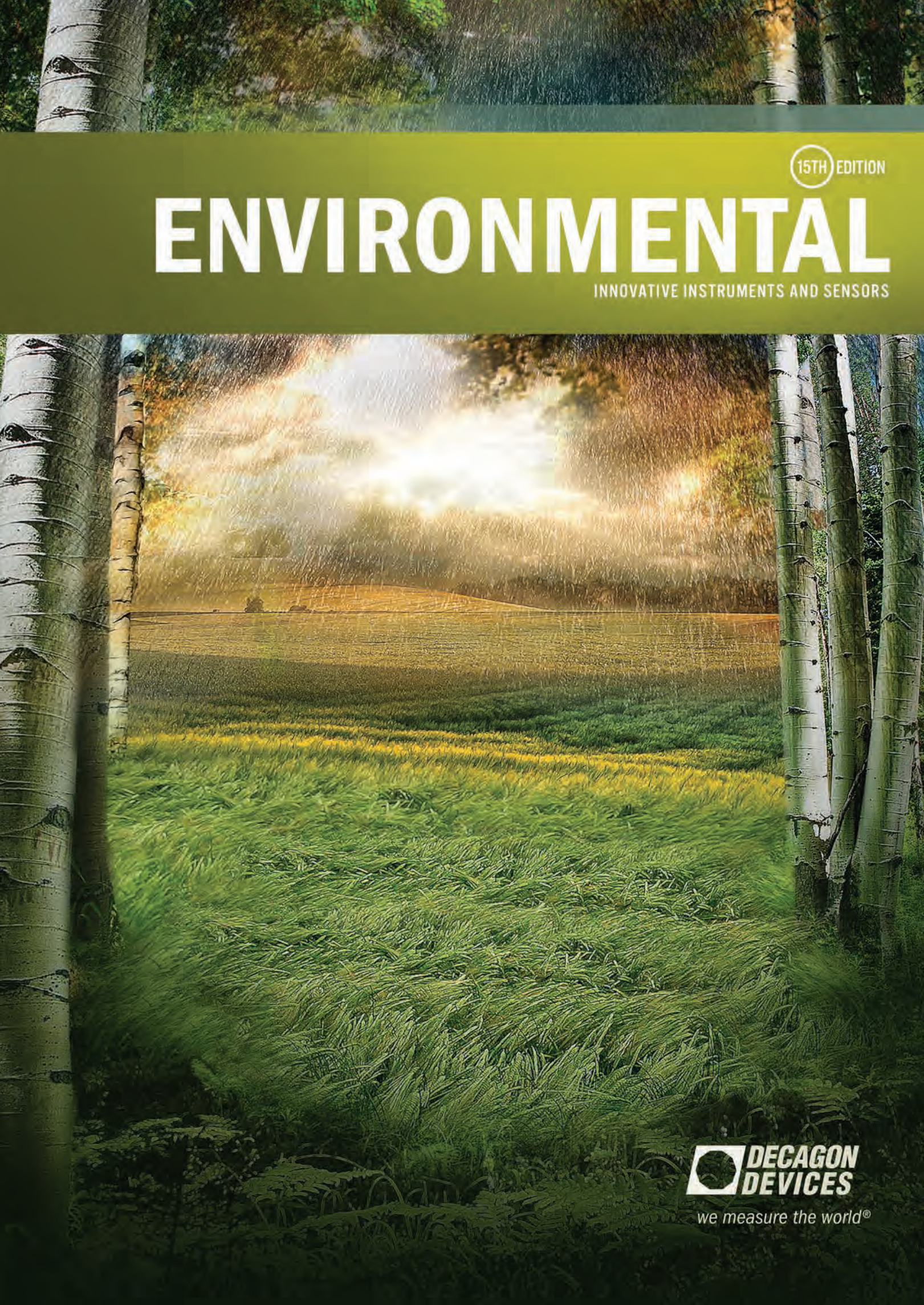


15TH EDITION

ENVIRONMENTAL

INNOVATIVE INSTRUMENTS AND SENSORS

DECAGON DEVICES

we measure the world®

New Instruments

8

DS-2 Sonic Anemometer
Ultrasonic accuracy, no moving parts, runs off 5 AA batteries.

28

CTD Water Conductivity, Temperature and Depth Sensor
New models go to 5 and 10 meter depths and don't require maintenance even when they dry out.

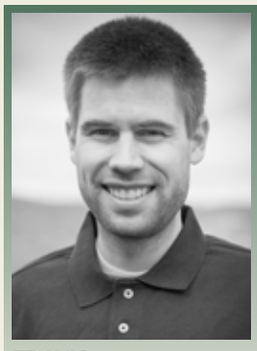
25

Smart Field Lysimeter
A weighing lysimeter you can transport in a pickup truck and install by hand.

5

SRS Multiband Radiometer
Field-rugged and matchbox-sized for continuous NDVI and PRI at the plot or plant scale.

Service



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Contents

SC-1

Leaf Porometer

The leaf porometer measures stomatal conductance using a sensor head with a fixed diffusion path to the leaf.

Applications

- Plant ecophysiology
- Plant water stress
- Leaf transpiration
- Stomatal conductance
- Ecosystem water balance
- Herbicide uptake

Steady State Design–
No fans, tubes, or pumps.

- **Automated**
  Eliminates user subjectivity
- **Low power**
  Runs on four AA batteries
- **Lightweight**
  Weighs about 300 g

- **Reliable data**
  Uses purely first principles method, desiccant chamber improves readings
- **Easy**
  Operate sensor head one-handed
- **Straight forward**
  No knobs to twist, no parameters to adjust
- **Small**
  Controller fits in the palm of your hand

Specifications

Conductance range: 0 to 1000 mmol m^{-2} s^{-1}. **Accuracy:** +/- 10%. **Operating environment:** 5 to 40 °C, 0 to 100% RH, non-condensing. **Units:** mmol $m^{-2}s^{-1}$, m^2s mol^{-1}, s/m. **Sample chamber aperture:** 6.3 mm. **Sensor head cable length:** 1.2 m. **Measurement time in auto mode:** 30 s. **Power:** Four AA alkaline batteries. **Data storage:** 4095 measurements in flash memory.

Mathematics of the Steady State Porometer

Decagon's Steady State Porometer measures stomatal conductance using a sensor head with a fixed diffusion path to the leaf. It measures the vapor concentration at two different locations in the diffusion path. It computes vapor flux from the vapor concentration measurements and the known conductance of the diffusion path using the following equation:

$$F_{vapor} = \frac{C_{vL} - C_{v1}}{R_{vs} + R_1} = \frac{C_{v1} - C_{v2}}{R_2}$$

Where C_{vL} is the vapor concentration in the leaf, C_{v1} and C_{v2} are the concentrations at the two sensor locations, R_{vs} is the stomatal resistance, R_1 is the resistance of the air between the leaf, and R_2 is the resistance between the two sensors. If the temperatures of the two sensors are the same, vapor concentration can be replaced with relative humidity, giving

$$R_{vs} = \frac{1 - h_1}{h_2 - h_1} R_2 - R_1$$

Where h_1 and h_2 are relative humidities at the two sensor locations. Conductance is the reciprocal of resistance, so

$$C_{vs} = \frac{1}{R_{vs}}$$

learn.decagon.com/porometer

Watch a 3 minute video to see how the SC-1 uses first-principle methods to measure stomatal conductance.

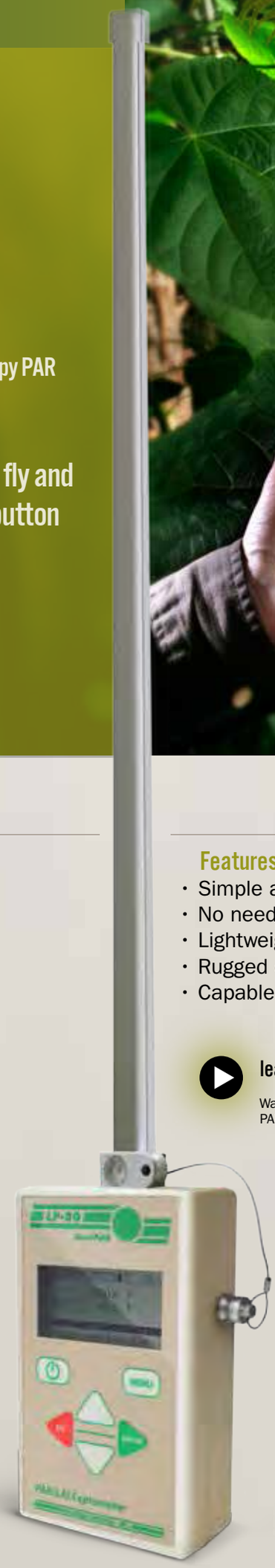
LP-80

Ceptometer

The LP-80 automatically calculates:

- Above and below canopy PAR
- LAI - Leaf Area Index
- τ - ratio between, below, and above canopy PAR
- F_b - fraction beam radiation

All output variables are calculated on the fly and displayed on the user interface. Press a button to log values (~2000 data points).



Includes:

- **External PAR Sensor**
  2 meter cable with connector to the ceptometer's external port. Calibrated to provide an output of about 0.1 mV per µmol m^{-2} s^{-1} (calibration label provided).

- **RS-232 cable**
  For interfacing between your computer and the ceptometer.

- **Carrying case**
  Polyethylene hardened case with custom foam cutouts allow the instrument and its accessories to be safely stored inside. 3.6 kg, 11.8 x 24 x 109 cm.

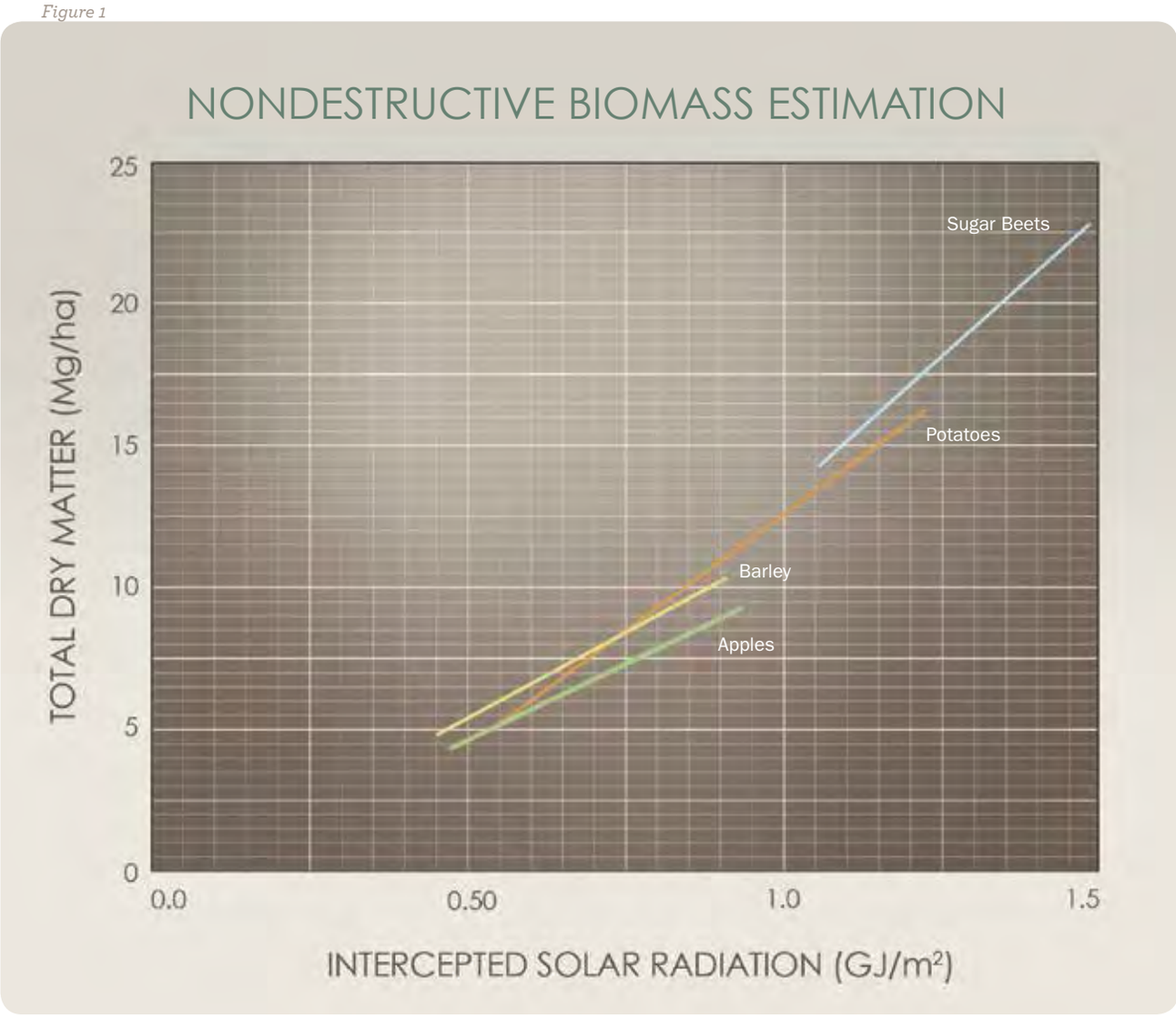
Features:

- Simple and intuitive operation
- No need for post processing data
- Lightweight and portable
- Rugged design made for field applications
- Capable of manual or unattended operation

learn.decagon.com/LP80

Watch a two minute video on measuring PAR and LAI with the AccuPar LP-80.

Figure 1



Use transmitted PAR data to estimate biomass production without destroying the canopy.

The conversion of light energy and atmospheric carbon dioxide to plant biomass is fundamentally important to both agricultural and natural ecosystems. The detailed biophysical and biochemical processes by which this occurs are well understood.

At a less detailed level, though, it is often useful to have a simple model that can be used to understand and analyze parts of an ecosystem.

Such a model has been provided by Monteith (1977). He observed that when biomass accumulation by a plant community is plotted as a function of the accumulated solar radiation intercepted by the community, the result is a straight line. Figure 1 shows Monteith's results.

Specifications

Operating environment: 0 to 5°C, 0 to 100% relative humidity. **Probe length:** 86.5 cm. **Number of sensors:** 80. **Overall length:** 102 cm (40.25 in). **Microcontroller dimensions:** 15.8 x 9.5 x 3.3 cm (6.2 x 3.75 x 1.3 in). **PAR range:** 0 to >2,500 µmol m^{-2} s^{-1}. **Resolution:** 1 µmol m^{-2} s^{-1}. **Minimum spatial resolution:** 1 cm. **Data storage capacity:** 1MB RAM, 9000 readings. **Unattended logging interval:** User selectable, between 1 and 60 minutes. **Instrument weight:** 1.22 kg (2.7 lbs). **Data retrieval:** Direct via RS-232 cable. **Power:** 4 AA Alkaline cells. **External PAR sensor connector:** Locking 3-pin circular connector (2 m cable). **Extension cable option:** 7.6 m (25 ft).

SRS

Spectral Reflectance Sensor

The SRS Spectral Reflectance Sensor is a rugged multiband radiometer that measures either Normalized Difference Vegetation Index (NDVI) or Photochemical Reflectance Index (PRI) continuously at the plot or plant scale.

Applications

NDVI and PRI are correlated with canopy variables such as:

- Leaf area index
- Light interception
- Light use efficiency
- Biomass and crop yield
- Crop and forest phenology
- Canopy growth
- Photosynthetic performance
- CO_2 uptake

Built for Unattended Monitoring

Watertight, weatherproof housing and fully sealed optics mean the SRS can be deployed in the field for an entire growing season or longer.

Low Cost

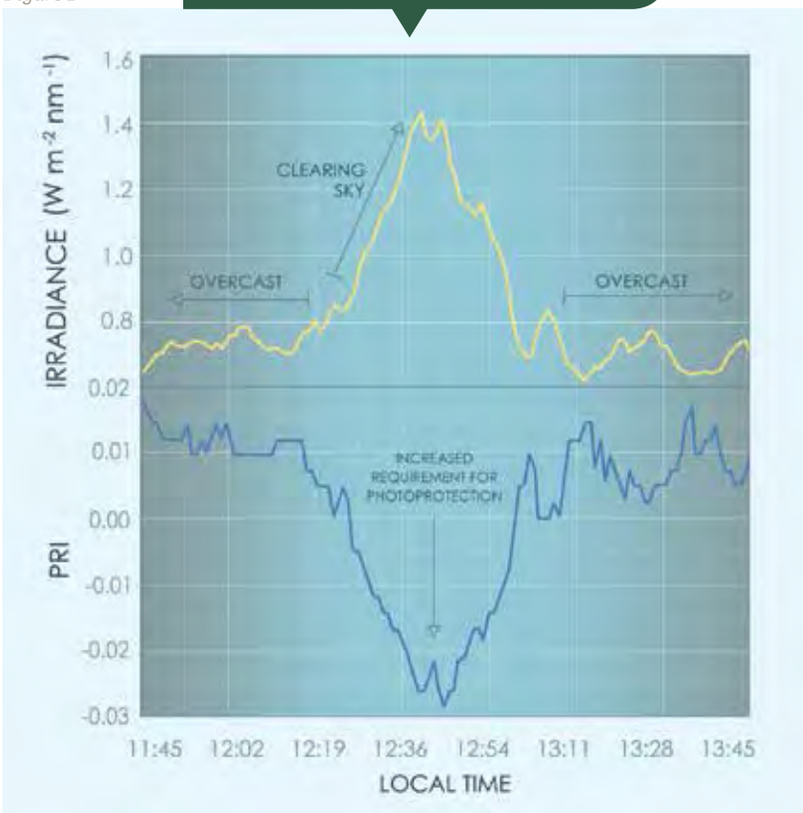
Rugged, low cost, research-grade sensors let you explore spatial and temporal variability of canopy structure and function.

Collect High Spatial Resolution NDVI or PRI Continuously

Satellite and aircraft-derived spectral vegetation indices are produced as snapshots in time and have relatively coarse spatial resolutions. The SRS is designed to be mounted directly above the plant or canopy of interest and provides a continuous stream of NDVI or PRI data for as long as it is mounted in the field.

Use PRI to estimate light use efficiency

Figure 1



Specifications

Accuracy: 10% or better for spectral irradiance and radiance values. **Dimensions:** 43 x 40 x 27 mm. **Calibration:** NIST traceable calibration to known spectral irradiance and radiance. **Measurement Time:** < 300 ms. **Connector Type:** 3.5 mm (stereo) plug or stripped and tinned wires. **Communication:** SDI-12 digital sensor. **Data logger compatibility:** (not exclusive) Decagon Em50 series, Campbell Scientific. **NDVI bands**: Centered at 630 nm and 800 nm with 50 nm and 40 nm Full Width Half Maximum (FWHM), respectively. **PRI bands**: Centered at 532 nm and 570 nm with 10 nm FWHM.

SRS sensors are designed to be in a dual view arrangement (up and down looking) for continuous measurement of percent reflectance.

Percent reflectance is the ratio between reflected and incident radiation, measured using downlooking (Figure 1) and uplooking (Figure 2) sensors, respectively. Depending on spatial variability in sky conditions, one uplooking sensor to provide reference values for multiple downlooking sensors.

Connect and Collect: Em50 Data Loggers.
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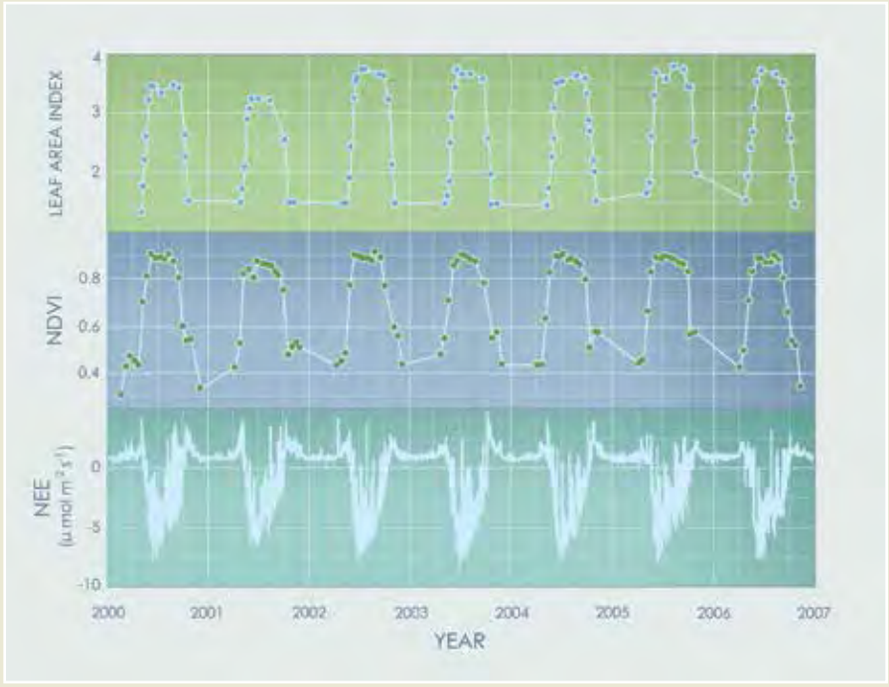
Figure 3



Use NDVI to track changes in LAI and seasonal dynamics in ecosystem productivity (Figure 2).

LWS

Leaf Wetness Sensor

Detect Leaf Wetness Duration

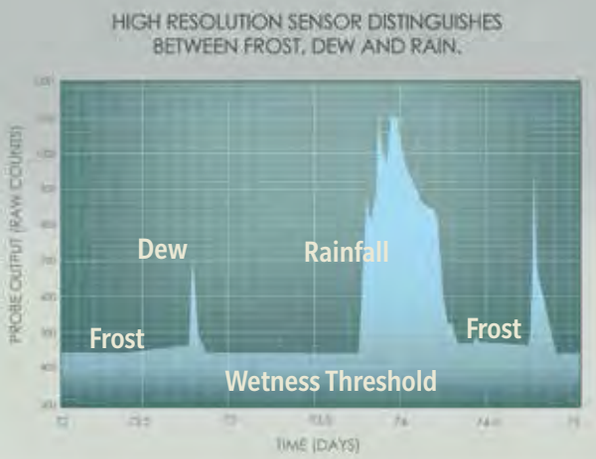
The Leaf Wetness Sensor (LWS) is mounted within a plant canopy to detect the presence of moisture on leaves in the canopy and to determine how long leaves remain wet.

learn.decagon.com/LWS

Watch a 4 minute video on the unique measuring capabilities of the Leaf Wetness Sensor.

Applications:

- Disease forecasting, modeling, and prevention.
- Ecological and agricultural research.
- Estimate canopy intercepted precipitation.
- Crop and orchard management.



Mimics a real leaf

The LWS gains accuracy by closely approximating the thermal mass and radiative properties of natural leaves.

Detects dew and frost

Sensor output is proportional to the amount of water on the sensor surface, so you can pinpoint frost, dew, and rainfall.

Measurement is not resistance based

Rather than measuring changes in resistance, the LWS measures the dielectric constant in a zone extending approximately 1 cm from the upper surface of the sensor. This means that the measurement is not dependent on having water droplets large enough to bridge a gap. It also means no calibration or painting is needed, making the LWS easier to set up and maintain compared to other leaf wetness sensors.

Specifications

Measurement Speed: 10 ms. **Sensor Type:** Frequency domain. **Output:** 320 - 1000 mV @ 3 V excitation. **Operating environment:** -40°C to 50°C. **Expected lifetime:** 2+ years continuous use. **Power:** 2.5 VDC @ 2 mA, to 5 VDC @ 7 mA. **Cable Length:** 5 m standard, custom lengths available. **Connector Type:** 3.5 mm “stereo” plug or stripped and tinned lead wires. **Dimensions:** 11.2 cm x 5.8 cm x .075 cm. **Data logger compatibility:** Decagon’s Em50 series loggers and Campbell Scientific loggers.

* When read with the Em50 data logger, the LWS outputs 445 raw counts when dry. When wet, counts are proportional to the amount of water on the sensor surface.

Applications:

- Characterize microclimate
- Model PET and ET
- Surface-atmosphere energy exchange
- Transport of mass and energy (particulate matter, gases, heat)
- Monitor fertilizer/pesticide herbicide applications
- Fire weather assessment, fire behavior forecasting
- Mobile sampling platforms

DS-2

Sonic Anemometer

Measure Wind Speed, Direction and Maximum Gust

The DS-2 is a simple, compact sonic anemometer that measures horizontal wind speed, direction and maximum gust. The DS-2 is a rugged, research grade sensor.

Accurate at Low Wind Speeds

The DS-2 has a lower measurement threshold of 0 m/s. Because of friction, cup anemometers have a lower measurement threshold of 0.5 m/s.

Never Needs Calibration

Sonic anemometers use ultrasonic sound waves to measure wind velocity. Because the measurement is founded on first principles, the sensor doesn't need calibration.

Requires No Maintenance

No moving parts to oil or replace.

Uses Very Little Power

Built to run for 6 months or more on the 5 AA batteries in your Em50 series data logger (also compatible with other data loggers).

Affordable

High accuracy and low per-sensor cost make acquiring vertical wind profiles and greater spatial coverage possible.

Specifications

Wind Speed
Range: 0 to 30 m/s. **Resolution:** 0.01 m/s. **Accuracy:** 0.30 m/s or 3%, whichever is larger.

Wind Direction
Range: 0 to 359 degrees. **Resolution:** 1 degree. **Accuracy:** ±3 degrees.

Dimensions
Diameter: 100 mm. **Sensor body height (w/mount):** 155 mm.

Communication: SDI-12. **Maximum sampling speed:** 1 Hz. **Connector types:** 3.5 mm (stereo) plug or stripped & tinned lead wires (pigtail). **Data logger compatibility:** Decagon's Em50 series loggers and Campbell Scientific loggers.

Connect and Collect: Em50 Data Loggers.
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Environmental Sensors

Characterize the Environment Above the Soil Surface

VP-3

Temperature, Relative Humidity, Vapor Pressure

Rugged stainless steel sensor measures the temperature of soil and other materials. Completely waterproof, submersible, and designed for continuous underground use.

Probe RH range: 0 to 100% RH.
Temperature range: -40 to 80°C.
Vapor Pressure range: 0-47 kPa.
Temperature accuracy: ±1°C.
RH accuracy: ±2% from 10–90% RH, ±3% from 0–10% RH, and 90–100% RH.

Complete accuracy specifications online.

Cup Anemometer

Wind Speed and Direction

Measures both wind speed (using windcups and a magnetic switch) and wind direction (with wind vane). Includes sealed stainless steel bearings for long life. The range and accuracy specifications of this unit have been verified in wind-tunnel tests (information available upon request).

Resolution: 0.45 m/s (1 mph).
Range: 0 to 129 mph.
Accuracy: ±5%.

PAR Photon Flux Sensor or Pyranometer

Total Solar Radiation or Photosyntetically Active Radiation

Both sensors are completely water proof, submersible and designed for continuous outdoor use.

Cable length: 5 m.
PAR Range: 0 to 2000 µmol/m^2s.
PYR Range: 0 to 1750 Wm^{-2}.
Dimensions: 24 mm diameter, 29 mm height.
Accuracy: ±5%.

Our environmental sensors allow you to measure key variables for modeling evapotranspiration or can be used in combination with other above or below ground sensors to better understand processes that are linked across the soil-plant-atmosphere continuum. Measure relative humidity, precipitation, PAR, wind speed, and more.

RT-1

Soil Temperature

Rugged Stainless steel sensor measures the temperature of soil and other materials. Completely waterproof, submersible, and designed for continuous underground use.

Resolution: 0.1°C.
Range: -40 to 80°C.
Temperature accuracy: ±1°C.
Type: Thermistor.

ECRN-100

High-Resolution Rain Gauge

High-resolution rain gauge with 0.2 mm (0.01 in) resolution.

Resolution: 0.2 mm.
Funnel size 17x14.2 cm.

ECRN-50

Low-Resolution Rain Gauge

Small self-emptying rain gauge for measuring irrigation events or precipitation.

Resolution: 1 mm.
Funnel size: 5x10 cm.

ProCheck

Handheld Reader for all Decagon Sensors

Indispensable tool for large installations. This staff favorite allows you to:

- Take an instantaneous reading of any Decagon sensor.
- Check summary statistics.
- Know if the installation is good before you start backfilling.
- Troubleshoot sensors in the field.
- Set SDI-12 addresses.
- Store data from field.

Connect and Collect: Em50 Data Loggers.
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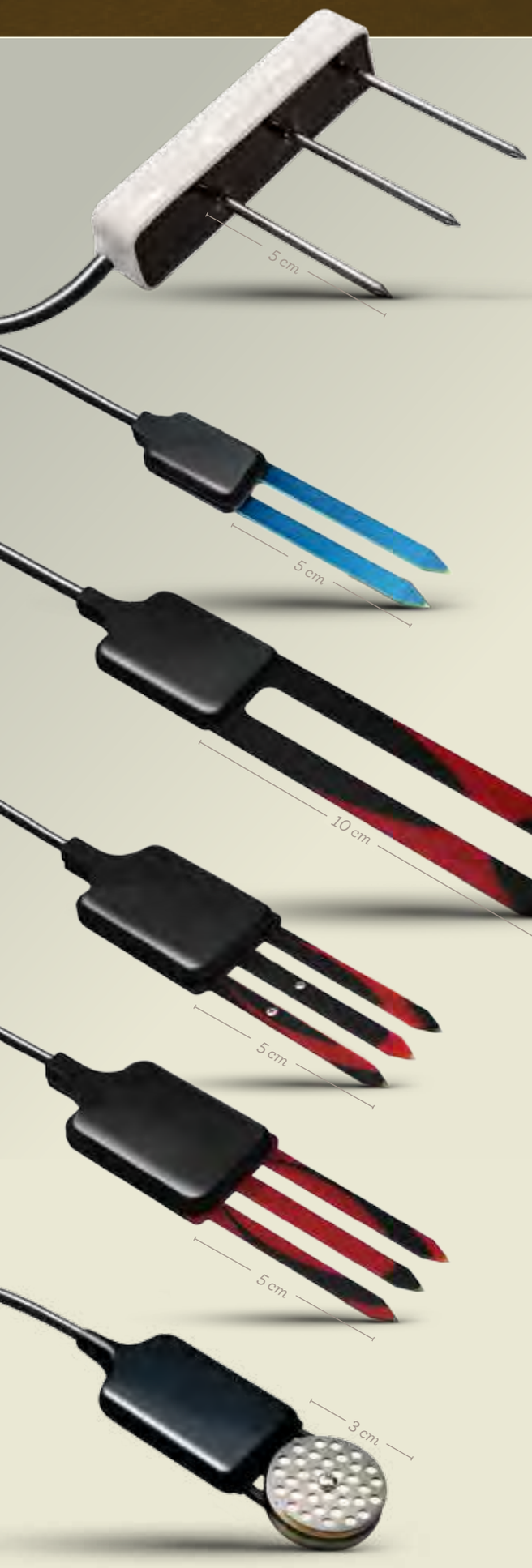
Research Grade, Publication Ready

Soil Moisture Sensors



Measurement & Benefits	Range	Accuracy
GS3 Volumetric Water Content, Electrical Conductivity, Dielectric Permittivity, Temperature. Benefits: Rugged stainless steel and epoxy design, SDI-12 compatible.	VWC: 0–100%. Apparent dielectric permittivity (ε_a): 1 (air) to 80. EC: 0 to 25 dS/m (bulk). Temperature: -40 to 50°C.	VWC: ±3%, typical mineral soils up to 8 dS/m. (ε_a): ±1 ε_a (unitless) from 1–40 (soil range), ±15% from 40-80. EC: ±5% from 0 to 5 dS/m, ±10% from 15 to 23 dS/m. Temperature: ±1°C.
EC-5 Volumetric Water Content. Benefits: All purpose, least expensive soil moisture sensor.	VWC: 0–100%.	VWC: ±3%, typical mineral soils up to 8 dS/m. VWC Rockwool: ±3% VWC, 0.5 to 8 dS/m. VWC Potting soil: ±3% VWC, 3 to 14 dS/m.
10HS Volumetric Water Content, Dielectric Permittivity. Benefits: Largest volume of influence decreases effects of heterogeneity.	VWC: 0–57%. Apparent dielectric permittivity (ε_a): 1 (air) to 50.	VWC: ±3%, typical mineral soils up to 8 dS/m. (ε_a): ±1 from ε_a of 2 to 10. ±2.5 from ε_a of 10 to 50.
5TE Volumetric Water Content, Electrical Conductivity, Dielectric Permittivity, Temperature. Benefits: Manage salts and fertilizers in your system, SDI-12 compatible.	VWC: 0–100%. Apparent dielectric permittivity (ε_a): 1 (air) to 80. EC: 0 to 23 dS/m (bulk). Temperature: -40 to 50°C.	VWC: ±3%, typical mineral soils up to 8 dS/m. (ε_a): ±1 ε_a (unitless) from 1–40 (soil range) ±15% from 40–80. Bulk EC: ±10% from 0 to 7 dS/m, user calibration required above 7dS/m. Temperature: ±1°C.
5TM Volumetric Water Content, Dielectric Permittvity, Temperature. Benefits: Include temperature dependencies in your research study, SDI-12 compatible.	VWC: 0–100%. Apparent dielectric permittivity (ε_a): 1 (air) to 80. Temperature: -40 to 50°C.	VWC: ±3%, typical mineral soils up to 8 dS/m. (ε_a): ±1 ε_a (unitless) from 1–40 (soil range) ±15% from 40–80. Temperature: ±1°C.
MPS-2 Soil Matric Potential, Temperature. Benefits: Maintenance-free water potential and soil temperature monitoring measurements that do not drift over time, SDI-12 compatible.	Soil water potential (Ψ): -10 to -500kPa (pF 2.01 to pF 3.71). Temperature: -40 to 50°C.	Ψ: ±25% of reading from -10 to -100 kPa.* Temperature: ±1°C. **Accuracy significantly improved with custom calibration.*

Decagon's first soil moisture sensors were built to produce TDR-quality data without the cost and complexity. Over thirteen years, we've refined and extended the technology.

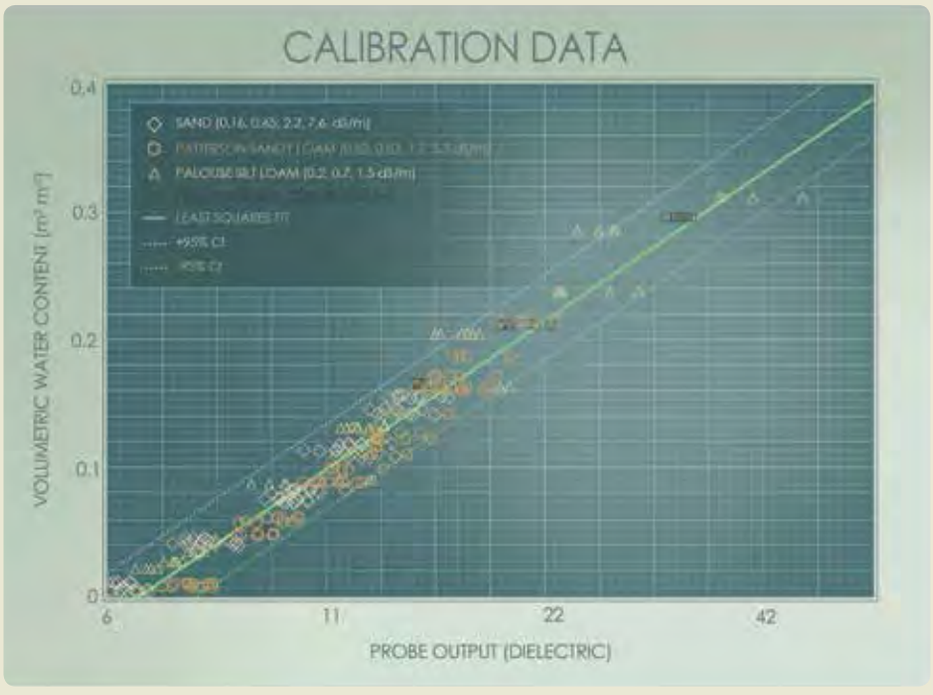
Hundreds of thousands of sensors later, today's ECH$_2$O soil moisture probes are:

- Publication ready: literally thousands of peer-reviewed publications use Decagon soil moisture probes
- Not sensitive to soil salinity and soil texture in typical soils
- Calibrated in a variety of soils for accurate results under actual field conditions
- Plug-and-play with Decagon data loggers no programming necessary

Calibrated in a variety of soils for accurate results.

Decagon has experimental sites and a soils lab to test how these sensors work in a variety of soils and under real growing conditions.

Decagon's soil moisture sensors are calibrated using four different soil textures with varying EC values.



Decagon's factory calibration integrates samples from clay, silt loam, sandy loam, and sand at a wide variety of EC values. The only time that you might need to do a custom calibration is if you're in a non-typical soil, in soils with high electrical conductivity (about 8 dS/m) or you need better than +-3% accuracy. We'll teach you how to do these custom calibrations at learn.decagon.com/custom-calibration.

Connect and Collect: Em50 Data Loggers.
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Questions about the data?

Contact Decagon for additional calibrations for soilless substrates and other media.

Visit **learn.decagon.com/custom-calibration** for a white paper on doing a calibration for your specific soils.

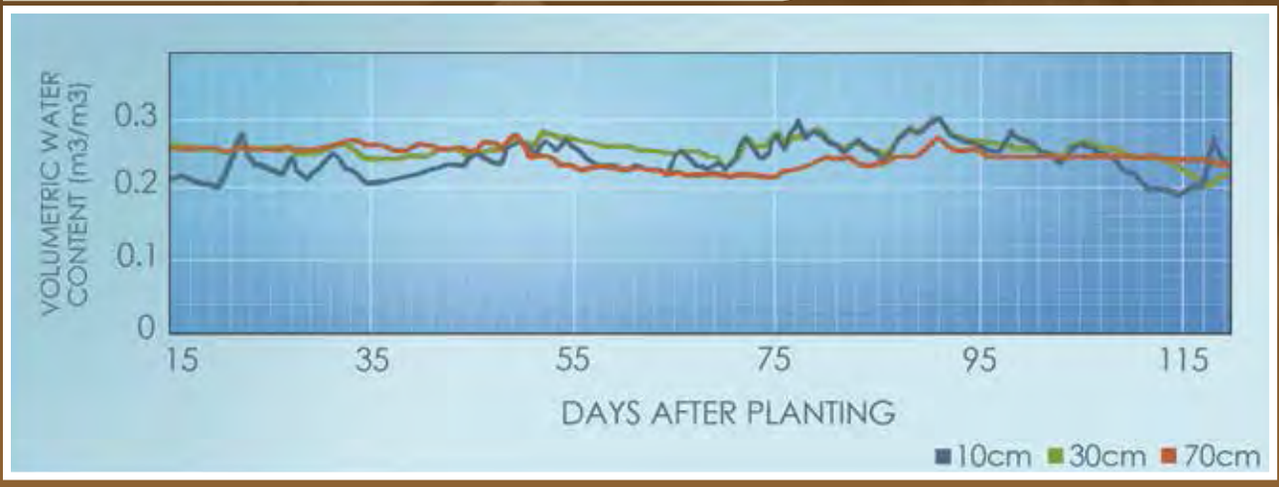
Where's the Fertilizer?

Using Electrical Conductivity to Tell the Rest of the Story

Electrical conductivity (EC) measurements go beyond soil moisture to show what is happening to salts in your soil profile. Consider the following Soil Moisture Data Only and Solution EC Values graphs:

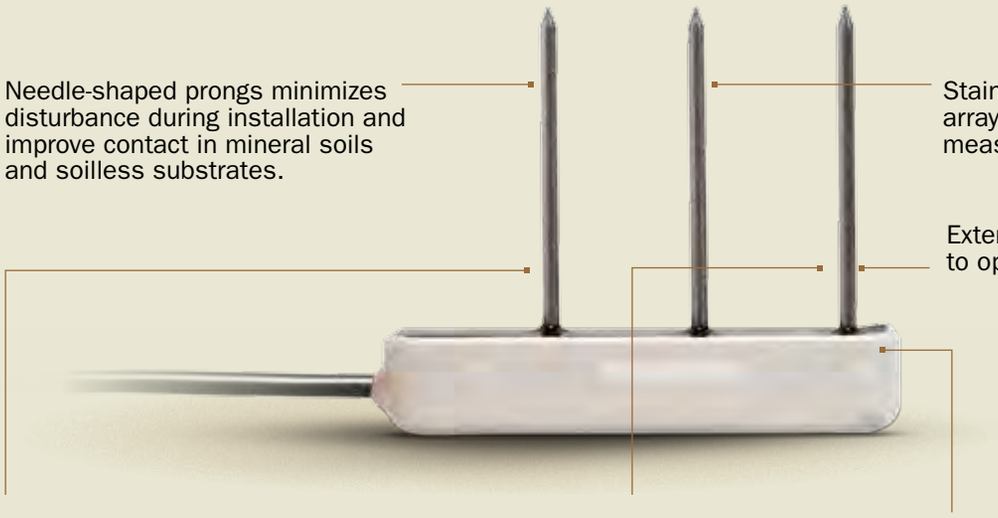
Soil Moisture Data Only

- No indication of nutrient leaching
- No indication of drainage



Soil water content values at three depths over time immediately following fertilization. But where's the fertilizer? Soil moisture values give no indication of nutrient leaching or drainage.

Sensors that measure EC | GS3



Needle-shaped prongs minimizes disturbance during installation and improve contact in mineral soils and soilless substrates.

Stainless steel electrode array for wider range of EC measurement (up to 20 dS/m)

Extended needle surface area to optimize EC measurements

70 MHz frequency (for dielectric measurement) minimizes salinity and textural effects for better accuracy

High frequency independent EC measurement allows 4-probe accuracy with a 2-probe sensor

Rugged epoxy encapsulation for extended life (10 years)

Connect and Collect: Em50 Data Loggers.
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Solution EC Values

- Clear indication of nutrient loss in EC data
- Clear indication of drainage

One Key Benefit: EC can help you track nutrient leaching.

Measurements of bulk EC and volumetric water content from a GS3 were used to calculate solution EC at the same three depths. Note how the fertilizer stays in the root zone temporarily, but is leached out during an irrigation event.

Sensors that measure EC | ES2

ES-2P version designed to be screwed into a T-connector to continuously measure conductivity of irrigation water

22 mm diameter to fit into tight spaces

Ruggedized sensor can survive freezing

Epoxy overmold allows sensor to remain continuously submerged

Four probe Wenner array measures up to 120 dS/m

Other Decagon Sensors that Measure EC:

5TE
Soil Moisture
Temperature
Electrical Conductivity
pg. 11

G3
Deep Drainage
Temperature
Electical Conductivity
pg. 27

CTD
Water Depth
Temperature
Electrical Conductivity
pg. 28

KD2 Pro

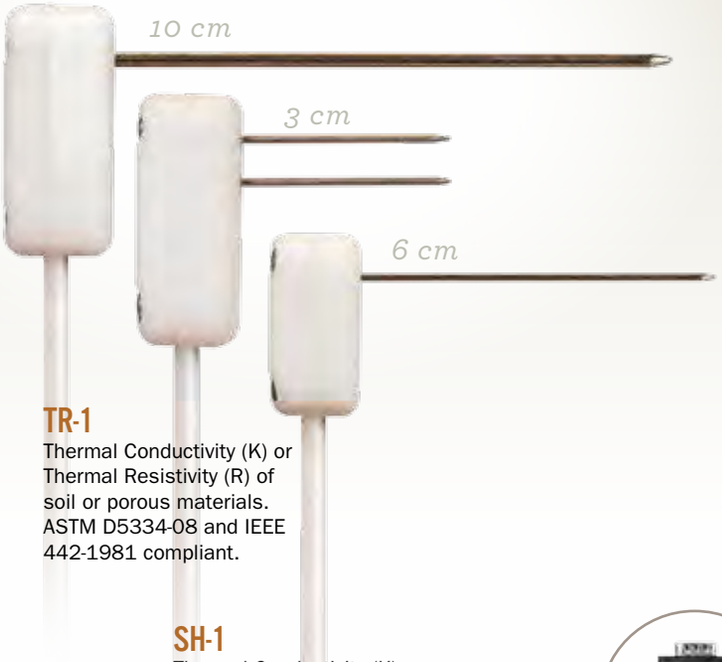
Model Heat Movement

Get A Handle On Heat Transfer.

EACH KD2 PRO COMES FACTORY CALIBRATED AND INCLUDES PERFORMANCE VERIFICATION STANDARDS

Measure heat transfer in the soil-plant-atmosphere continuum with the KD2 Pro Thermal Properties Analyzer. The KD2 Pro has three interchangeable sensors that measure thermal conductivity, thermal diffusivity, and specific heat (heat capacity), along with data storage capabilities and an automatic data collection mode.

- Heated Needle Technology.
- Requires No Calibration.
- Utility Software Allows for Data Downloads.
- Small Needle Minimizes Soil Disturbance.



TR-1

Thermal Conductivity (K) or Thermal Resistivity (R) of soil or porous materials. ASTM D5334-08 and IEEE 442-1981 compliant.

SH-1

Thermal Conductivity (K), Thermal Diffusivity (D), and Specific Heat (C).

KS-1

Thermal Conductivity (K) of liquids.

RK-1

Thermal conductivity/resistivity; for use with stone or cement samples.

The optional RK-1 sensor kit measures rock, concrete and other materials where drilling a pilot hole is required.

learn.decagon.com/KD2pro

Watch a three and a half minute video about measuring soil thermal conductivity with the KD2 Pro.

Specifications

Measurement time: 90 seconds to 10 minutes. **Accuracy***: Conductivity/Resistivity: ± 5 to ± 10%, Thermal Diffusivity: ± 10%, Specifi Heat: ± 10%. **Ranges*:** K: 0.02 to 4 Wm^{-1} C^{-1}, D: 0.1 to 1.0 mm^2s^{-1}, R: 0.5 to 50 mC W^{-1}, C: 0.5 to 4 MJ m^{-3} C^{-1}. **Data storage:** 4095 readings. **Sensor environment:** –50 to 150°C. **Case size:** 15.5 x 9.5 x 3.5 cm. **Power:** 4 AA Batteries **Cable:** 1 m.

**Accuracy and measurement range vary with sensor type.*

Thermal Resistivity of Porous Materials (Soils) Change with Changes in Density, Water Content, Temperature and Composition

Soils and other porous materials vary in density, water content, temperature and composition, which affects the thermal resistivity of porous material. Table 1 shows thermal properties of typical soil constituents. These constituents occur as mixtures in typical porous materials. The thermal resistivity of the mixture is quite difficult to compute, since it depends, not only on the thermal resistivities of the components, but also on their geometric arrangement. Methods for making this computation are given by Campbell and Norman (1998) and deVries (1963). These methods were used to compute the thermal resistivity of soils as they vary with water content, composition, density and temperature. The results of these computations are shown in Figures 1, 2 and 3.

In general, the thermal resistivity of a mixture is strongly influenced by the component with the highest resistivity. Dry quartz sand and dry loam soil have about the same resistivity, even though the resistivity of the minerals differs by a factor of 3 (Figure 1 and Table 1). As the limiting resistivity becomes larger, differences in the resistivities of the other components have a larger effect. For example, dry quartz and loam differ in resistivity by about 10%, while water saturated quartz sand has about half the resistivity of saturated loam (Figure 1).

As the water content of unsaturated porous materials increases, a threshold is reached where resistivity decreases rapidly with increasing water content. This is evident in all three figures. This threshold is more closely related to hydraulic than thermal properties of the material. It is the water content at which liquid water can flow across particle surfaces to re-evaporate and transport latent heat across pores in the medium.

In other words, the soil acts like a “heat pipe,” an engineering device which makes use of latent heat transport for rapid and effective heat transfer. In a moist soil at room temperature 10 to 20% of the total heat transport is as latent heat through the pores. This portion of the heat transport is strongly temperature dependent, roughly doubling for each 10°C temperature rise.

The effective thermal resistivity of moist, air-filled pores is about the same as the thermal resistivity of water at 60°C, so, at this temperature, changing the water content of the material does not affect its resistivity. In Fig. 3, the 50°C curve shows almost no change in resistivity with increasing water content once the water content is high enough to sustain the liquid return flow within the pores.

Figure 1

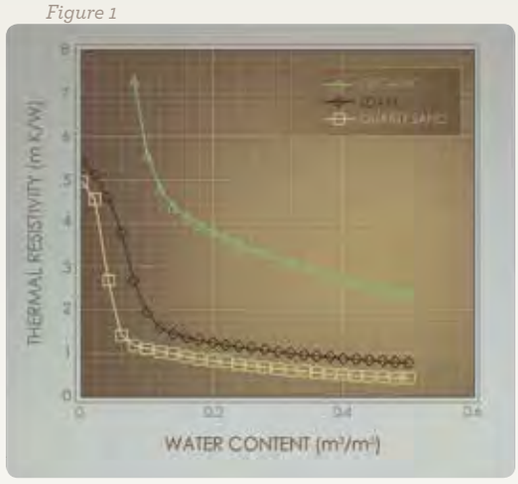


Figure 2

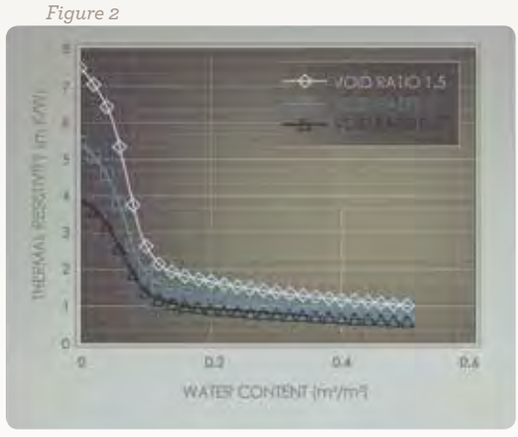


Figure 3

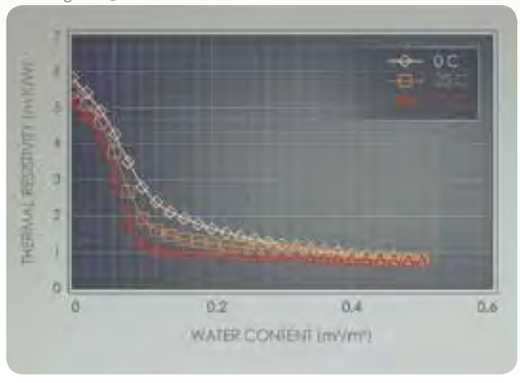


Table 1. Thermal properties of soil materials (T is Celsius temperature) [modified from Campbell and Norman, 1998]

MATERIAL	DENSITY ($M\ gm^{-3}$)	SPECIFIC HEAT ($J\ g^{-1}K^{-1}$)	THERMAL COND. ($W\ m^{-1}K^{-1}$)	THERM. RESISTIVITY ($m\ K\ W^{-1}$)
SOIL MINERALS	2.65	0.87	2.5	0.40
GRANITE	2.64	0.82	3.0	0.33
QUARTZ	2.66	0.80	8.8	0.11
GLASS	2.71	0.84	1.0	1.00
ORGANIC MATTER	1.30	1.92	0.25	4.00
WATER	1.00	4.18	0.56+0.0018T	1.65 @25C
ICE	0.92	2.1+0.0073T	2.22-0.011T	0.45 @ 0C
AIR (101 kPa)	$(1.29\text{-}0.0041T * 10^{-3})$	1.01	0.024+0.00007T	38.8 @25C

1. Campbell, G. S. and J. M. Norman. 1998. An Introduction to Environmental Biophysics, 2nd Ed. Springer Verlag, New York.
2. Campbell, G. S., J. D. Jungbauer, Jr., W. R. Bidlake and R. D. Hungerford. 1994. Predicting the effect of temperature on soil thermal conductivity. Soil Sci. 158:307-313
3. De Vries, D. A. 1963. Thermal properties of soil. In Physics of Plant Environment. W. R. van Wijk (ed.) North Holland Pub. Co. Amsterdam pp. 210-235

WP4C

Essential Water Potential Data

Measure the water potential of soil, soilless substrate, plant tissue, or any porous material in 5 to 10 minutes.

Measure water potential by determining the relative humidity of the air above a sample in a closed chamber.

Make fast, accurate water potential measurements in the lab.

AOAC-APPROVED METHOD, CONFORMS TO ASTM 6836

Applications:

- Soil moisture characteristic curves
- Root zone water potential profiles
- Expansive soil characterization
- Seed priming
- Seed water relations

WP4C New Features:

Precise Mode Verifies full equilibrium before displaying a final reading.

Speedy Equilibration New hydrophobic teflon impregnated nickel alloy sample chamber coating reduces equilibration time.

Finely-Tuned Adjustments New 24-bit ADC electronics allow precision calibration and ±0.05 MPa (or better) accuracy.

Better Range and Accuracy Resolves temperatures to a thousandth of a degree ˚C to push the functional range to -0.1 MPa.

learn.decagon.com/WP4C

Watch R&D scientist Dr. Doug Cobos discuss the advancements made with the new WP4C.

Specifications

Operating environment: 5 to 43°C (41 to 110°F). **Temperature control:** 15 to 40°C ±0.2°C. **Sensors:** 1. Infrared temperature 2. Chilled-mirror dewpoint. **Range:** 0 to -300 MPa*. **Accuracy:** ±0.05 MPa from 0 to -5 MPa, ±1% from -5 to -300 MPa. **Read time:** Typically 5 to 10 minutes. **Interface cable:** Serial cable (included). **Data communications:** RS232 compatible, 8-bit ASCII code, 9600 baud, no parity, 1 stop bit. **Weight:** 3.2 kg (5.2 kg shipping weight). **Universal power:** 110-220V AC, 50/60Hz. **Sample size:** 7 ml. **Calibration standard:** 0.5 molal KCl (-2.22MPa).

25 plastic cups and 10 stainless steel cups included.

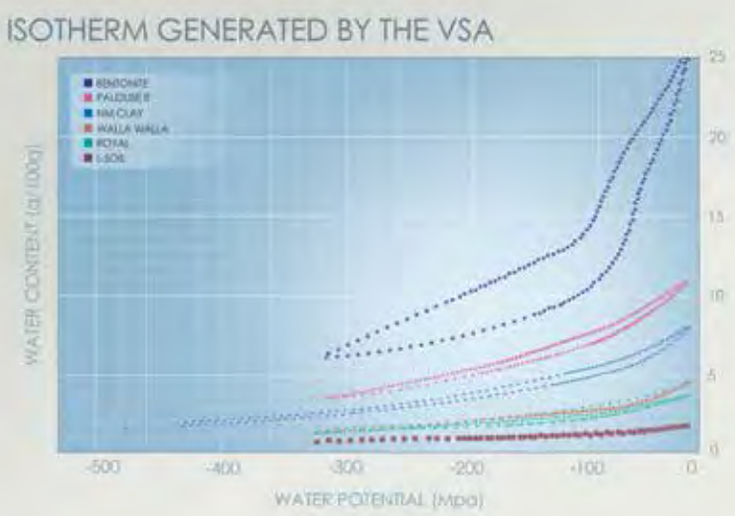
* *WP4C will read to 0 MPa, but readings of samples wetter than -0.1 MPa will have an increasing, and typically unacceptable, percentage of error. Some users may be able to make useful measurements in samples wetter than -0.1 MPa using special techniques. For more information, see the WP4C User Manual.*

VSA

Vapor Sorption Analyzer

Rapid isotherm generation

Fast expansive soil characterization



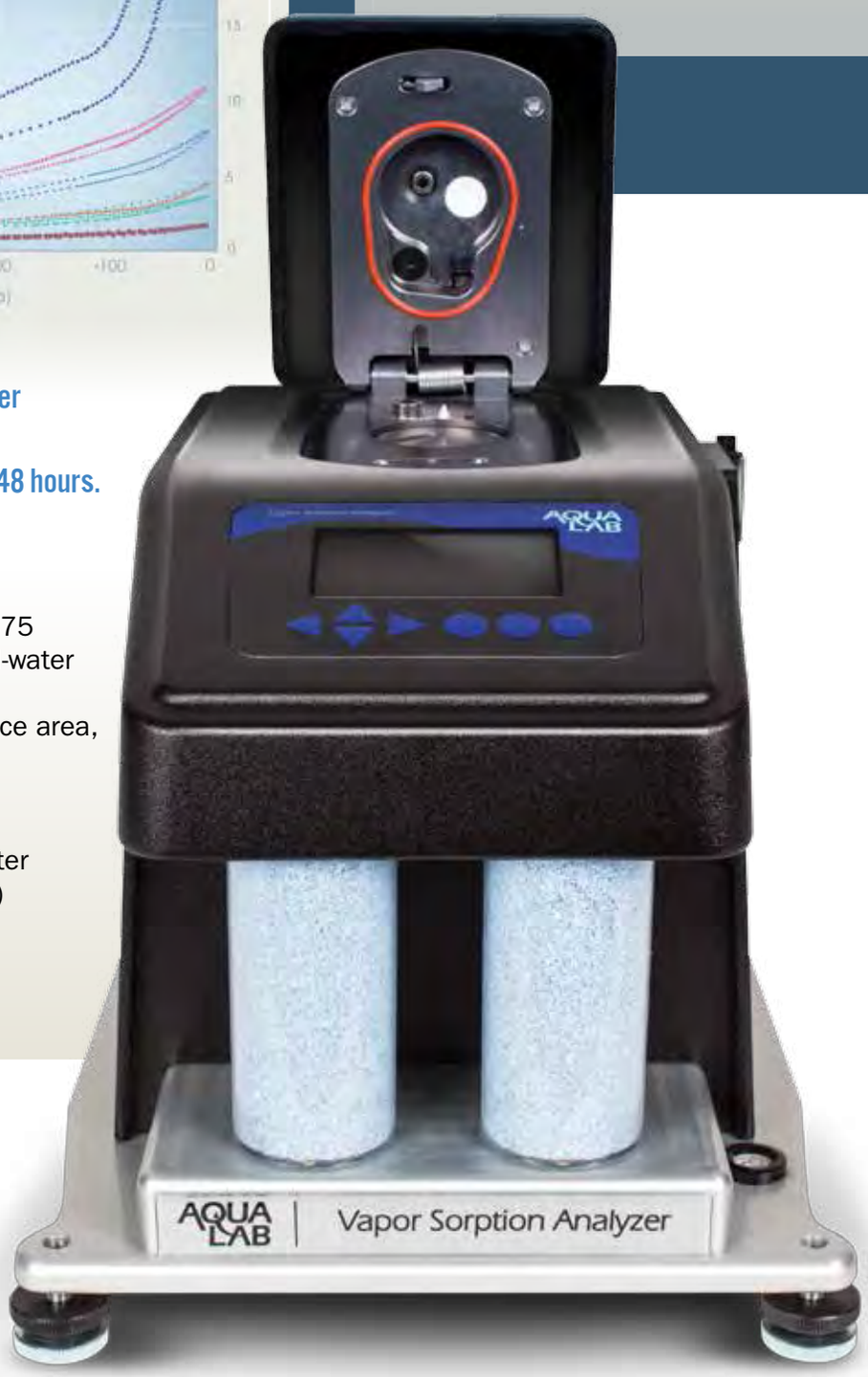
Applications:

- Expansive Soil Characterization
- Soil Water Characteristic Curves
- Vapor Sorption Dynamics

Generates up to 200 data points (water potential vs. water content) for both adsorption and desorption within 24 - 48 hours.

The VSA works in the dry (-10 to -475 MPa) range. Create automated soil-water characteristic curves and generate correlations with clay activity, surface area, and swelling potential.

Hold humidity constant and look at the kinetics of soil taking up water into its crystal structure (2:1 clays) and monitor water content change over time.



learn.decagon.com/VSA

Specifications

Range: -10 to -475 MPa. **Accuracy:** ±1 MPa or ±1%. **Temperature operating range:** 15 to 40°C. **Size:** W 25.4 x L 38.1 x H 30.5 cm (10x15x12 in.) **Weight:** 19 kg.

HyProp

Moisture Characteristic curves in the Tensiometer Range

Forget the pain of using pressure plates. Use HyProp to generate detailed soil-water characteristic curves.

Just take your undisturbed sample, saturate the sample, insert the measurement head, place the HyProp on the balance, and in less than a week, you have a detailed moisture release curve.

learn.decagon.com/fullcurve

Watch a short video on how the HyProp and WP4C work together.

Why Choose HyProp?

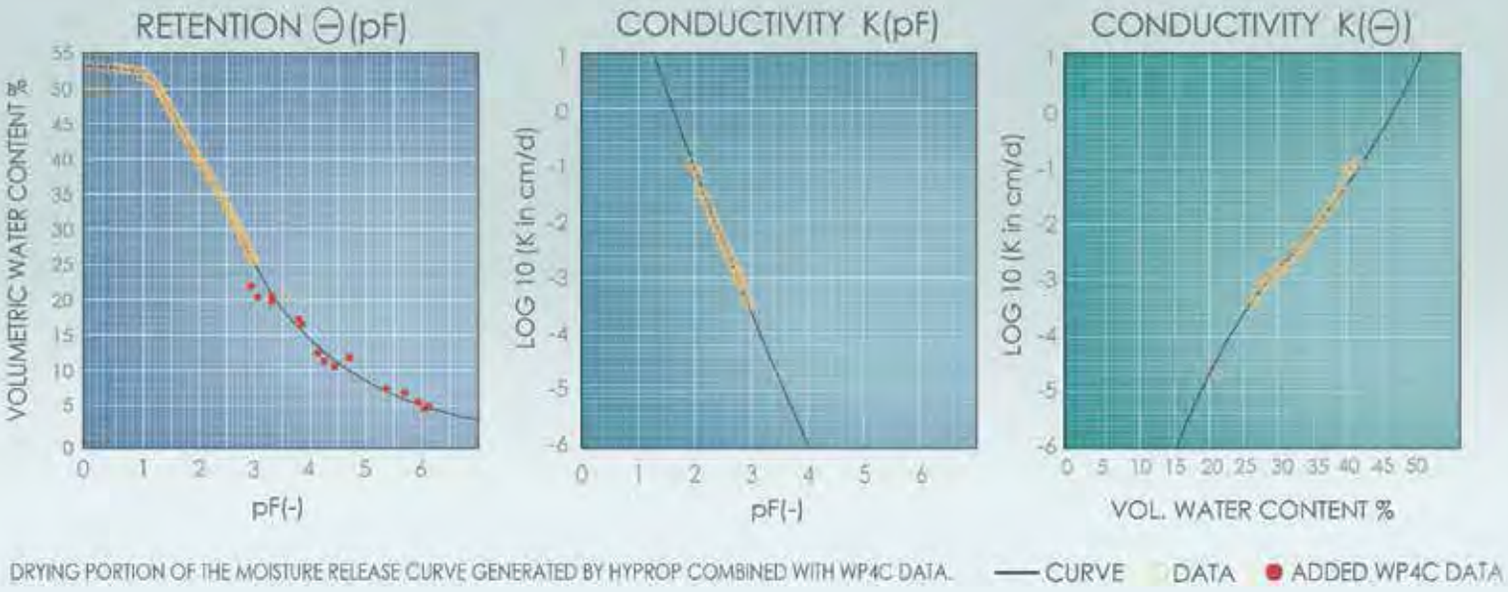
- Uses undisturbed soil samples.
- Works in all soil types.
- Bonus feature gives unsaturated hydraulic conductivity values for the soil sample.

Specifications

Range: +2 to -120 kPa / -250 kPa.
Resolution: 0.001 kPa.
Accuracy: ±0.15 kPa.

Optional Laboratory Scale Specifications
Measuring range: 0 to 2.5 kg.
Resolution: 0.01 g.
Accuracy: ±0.1 g.
Interface: RS232.

CREATE COMPLETE MOISTURE RELEASE CURVES WITH WP4C AND HYPROP



DRYING PORTION OF THE MOISTURE RELEASE CURVE GENERATED BY HYPROP COMBINED WITH WP4C DATA. — CURVE DATA ● ADDED WP4C DATA

Analyze all your data together.

HyProp-Fit Free Download
learn.decagon.com/hypropfit

HyProp-Fit software (a free download) makes it easy to use the HyProp with the new WP4C to generate a complete moisture release curve and parameters for use in modeling.

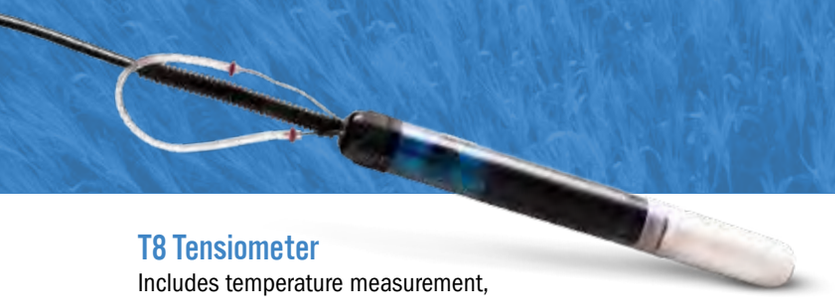
HyProp-Fit takes data generated by the HyProp, WP4C, tensiometer, or any other water potential instrument and creates a moisture release curve from the combined data.

Generate curve fits based on van Genuchten, van Genuchten Bimodal, Brooks and Corey, and other models. HyProp-Fit finds the optimal parameter sets without initial parameter guesses.

Tensiometers

Field Water Potential Monitoring

UMS designs and manufacturers tensiometers to make research easier. The pressure transducer-based sensors allow for precise measurement of water potential. A variety of sizes give you options for deployment from field to lab. Their newest tensiometer, the TS1, allows yearlong field deployment after installation.



T8 Tensiometer

Includes temperature measurement, refilling indicator and digital communication (SDI-12, RS485).

TS1

The world's first smart tensiometer. Designed to be deployed and left in the field, the TS1 logs water potential data, self refills, monitors temperature, and self-empties when the temperature nears freezing to avoid damage.

T5/T5x

Mini-tensiometers are essential for the measurement of water potential in small spaces such as soil columns, potted plants or laboratory water flow experiments.

T4 Tensiometer

Standard tensiometer with external refilling option.

Infield 7 Handheld

Digital display interfaces with all UMS tensiometers for spot measurements.

Tensiometer Specifications

Range: +100 to -85 kPa (-200 kPa T5x*). **Accuracy:** ±0.5 kPa. **Resolution:** 0.1 kPa. **Hysteresis:** typ. 0.1% FS. **Stability over one year:** typ. 0.5% FS. **Sensor:** Piezoresistive pressure transducer, overpressure max ±3000 hPa. **Electronics:** Wheatstone full bridge. **Compatibility:** Infield 7 and Campbell Scientific data loggers.

** This range is possible with the T5x only, depending on refill.*

Related Instrument

MPS-2

Water potential monitoring in vadose zone, crop stress, waste water drainage studies, irrigation monitoring and control, and plant water availability.

SPECIFICATIONS PG. 11

Measure Soil Hydraulic Conductivity

Quantify spatial variability of soil hydraulic conductivity.

Water movement in soil is spatially variable

The Mini Disk Infiltrometer is a quick way to test hydraulic conductivity and infiltration rates.

Backpackable

Small, compact, and simple, the Mini Disk Infiltrometer is a true field instrument. It can be tossed into a backpack with a bottle of water.

Quick setup

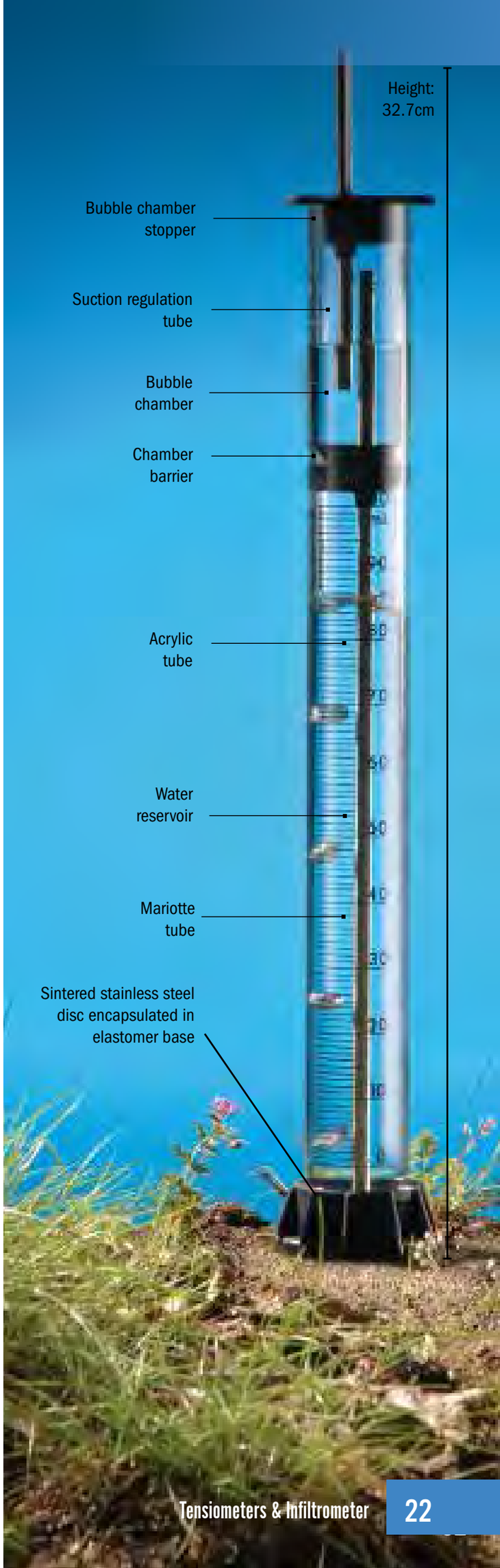
Just fill the reservoir, set the suction, and start measuring infiltration. You don't have to pre-saturate the disk.

Straightforward calculations

Enter infiltration and elapsed time data in the included spreadsheet calculator to find hydraulic conductivity ($K(\Psi)$).

Reliable

Both scientists and technicians have used the Mini Disk Infiltrometer to design irrigation systems, demonstrate hydraulic conductivity, evaluate erosion hazards, and gauge the impact of forest fires.



Specifications

Total Length: 32.7 cm. **Suction Range:** 0.5 to 7 cm of suction. **Water Volume for Operation:** 135 mL. **Diameter of Sintered Stainless Steel Disc:** 4.5 cm diameter, 3 mm width.

KSat

Measure Saturated Hydraulic Conductivity

The KSat is an instrument that measures the saturated hydraulic conductivity (Ksat) of soil samples. Hydraulic conductivity—the rate at which water flows through soil—is a key component in most models that simulate water flow, solute transport, and runoff.

THE KSAT IS BASED ON THE INVERSION OF DARCY'S LAW AND COMPLIES WITH DIN 19683-9 AND DIN 18130-1

Applications:

- Soil saturated hydraulic conductivity measurements
- Hydrology modeling
- Irrigation management
- Soil geotechnical testing
- Landfill cover infiltration testing

- **Completely integrated package**
  Everything you need, right out of the box.
- **Small footprint**
  Fully integrated to use minimal bench space.
- **Fully automated**
  No timing outflow, weighing beakers, or making judgement calls.
- **Better data**
  Improves accuracy by reducing user error.
- **Wide range**
  Conductivities from 10,000 to 0.1 cm/d.
- **Easy-to-use software**
  Performs all calculations.
- **Constant and falling head methods**

Specifications

Measurable Ksat values (min.): 0.1 cm/d (0.004 in/d). **Measurable Ksat values (max.):** 10000 cm/d (3937 in/d). **Hydraulic conductivity (Ks) of the porous plate:** 20000 cm/d (10000 in/d). **Pressure Sensor Accuracy:** 1 Pa (0.01 cm WC or 0.0001 psi). **Temperature sensor accuracy:** 0.2°C (0.4°F). **Sample ring (also fits with UMS HyProp) volume:** 250 mL (50 mm H X 80 mm i.d.). **Software requirements:** Windows 7 and later Microsoft Framework 3.5.

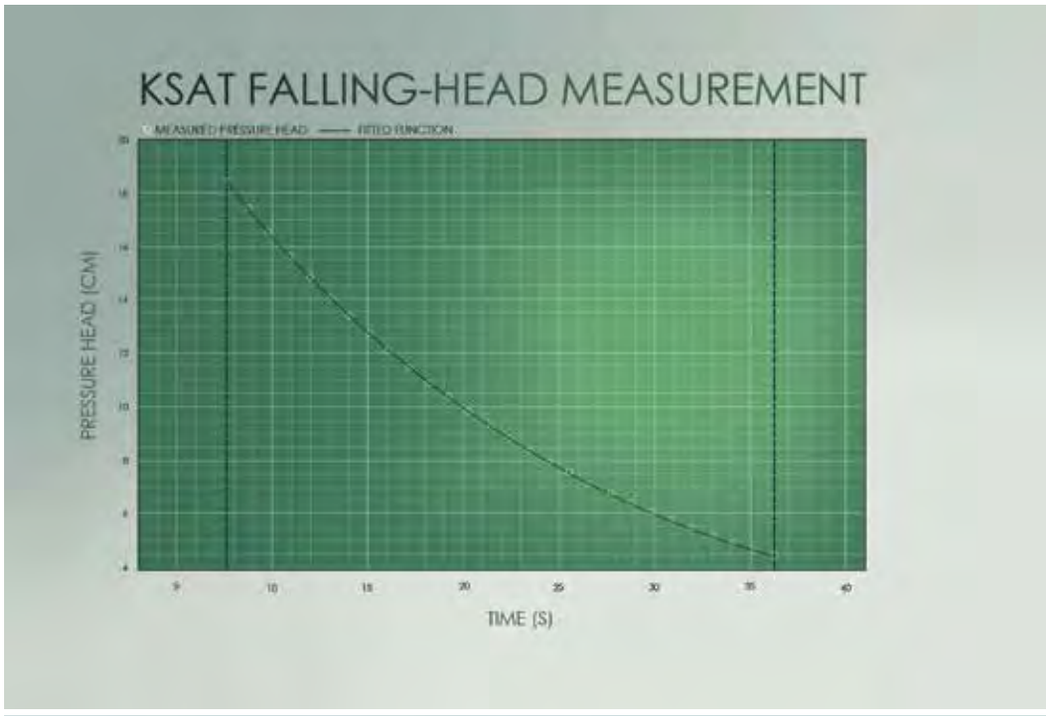
HyProp Completes the Picture

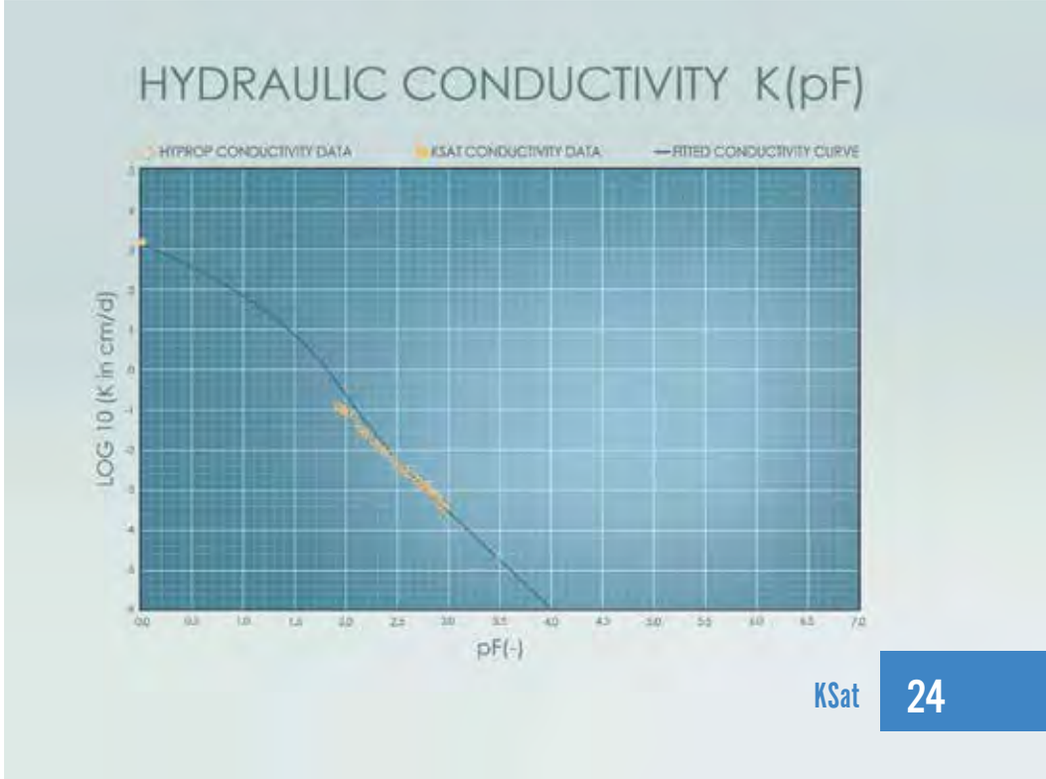
Unsaturated hydraulic conductivity is the most common flow state in soils, but it's not the most frequently measured hydraulic property.

Most models call for KSat values instead, possibly because KSat has traditionally been easier to measure.

Now, the HyProp makes unsaturated hydraulic conductivity as easy to measure as KSat.

Sample rings are interchangeable with the KSat, so the same sample can be used with each instrument.





Smart Field Lysimeter

Small Scale Weighing Lysimeter

The Smart Field Lysimeter is a modular weighing lysimeter that can be installed by hand. Up to four lysimeters can be operated by one control box.

Applications:

- Evapotranspiration studies
- Contaminant fate studies
- Climate change studies
- Developing crop coefficients
- Complete water balance studies

Turn-key solution

A weighing lysimeter in a box, complete with tensiometers, soil moisture sensors, data logger with GPRS modem, lightening protection, and solar panels.

High accuracyILoad cell

Gives an accurate water balance estimate.

Field identical soil tension

Soil tension is continuously adjusted at the lower boundary to match the native soil surrounding the lysimeter.

Can be self-installed

An optional installation tool set specifically designed for the Smart Field Lysimeter is available.

Affordable

Gives information on water and solute balance at a lower cost than a purpose-built, full-scale custom installation.

Collects leachate

Leachate is collected, weighed and stored for further analysis.

Minimizes site disturbance

The 30 cm diameter and removable collar minimize disruption of the natural environment.

30 cm 60 cm 90 cm

Available in 30, 60, and 90 cm lengths–with flexibility for customized layouts to suit different research needs and site limitations.

Lysimeter Weight Platform

Specifications

Lysimeter Height: 30, 60, or 90 cm. **Lysimeter Diameter & Material:** 30 cm; Stainless Steel.

COMPLETE LIST OF SPECIFICATIONS

www.decagon.com/lysimeter

Sensors involved in setup:

1 x T8 Field Reference Tensiometer

3 x 5TM Soil Moisture and Temperature

3 x MPS-2 Soil Matric Potential

Datalogger - DT80-M w/ Integrated GPRS/3G-modem

Power Supply - Rechargeable battery 12 V/26 Ah, Solar Panel and Power Management Module

PL-50/PL-100/PL-200 Weighing Platform for Lysimeter

PL-10 Weight Platform for Leachate Tank

G2/G3

Drain Gauge

Monitor Groundwater Leaching

Determine the volume of water and chemicals draining from the vadose zone into groundwater. The Drain Gauge measures drainage flux in unsaturated soils and collects soil water samples for chemical analysis.

An ingenious duct and wick design maintains a flow rate within the gauge equivalent to that in surrounding soil. A surface port allows you to draw out samples to analyze for chemicals, fertilizers, and other contaminants.

Applications:

- Waste landfill sites
  Advise operators when drainage is occurring and where cover systems need to be improved.
- Maximization of food processing waste applications
  Monitoring water drainage rates and water quality below the root zone.
- Environmental research
  Measuring percolation and recharge rates.
- Farming operations
  Measure and control irrigation during a cropping season.
- Recreational facilities
  Measure and control excess water and nutrient losses.
- Nitrate leaching

Connect and Collect: Em50 Data Loggers.
pg. 33

Drain Gauge G3
Sample Capture Technology

Surface port provides easy access to drainage, temperature and EC sensor for maintenance.

Drain Gauge G2
Flow Through Technology

Inert material construction of the tube, sensors, and collection reservoir inhibits chemical reactions.

G2 Specifications

Measurement surface area: 507 cm^2. **Sampling reservoir volume:** 3 L. **Accuracy:** ±10%. **Resolution:** 0.1 mm drainage. **Suction at intake:** 110 cm (11 kPa). **Total length:** 147 cm. **Divergence control tube (DCT) length:** 60 cm. **Measurement time:** 150 ms.

G3 Specifications

Measurement surface area: 324 cm^2. **Sampling reservoir volume:** 150 mL. **Accuracy:** ±10%. **Resolution:** 0.1 mm drainage. **Suction at intake:** 110 cm (11 kPa). **Total length:** 147 cm. **Divergence control tube (DCT) length:** 60 cm. **Measurement time:** 10 ms.

CTD

Conductivity, Temperature, Depth

The CTD is a submersible sensor that allows you to continuously monitor groundwater and surface water level changes along with electrical conductivity and temperature.

Decagon's CTD sensor puts much of its complex circuitry in an above-ground data logger. This lowers the per-sensor cost without impacting accuracy and resolution. So instead of relying on a single measurement, you can measure in several different locations without exceeding your budget.

Applications:

- Aquifer recharge and recovery.
- Saltwater intrusion, desalination, and wastewater.
- Wetland monitoring.
- Groundwater contamination monitoring.
- Surface water monitoring.

Connect and Collect: Em50 Data Loggers.
pg. 33

learn.decagon.com/CTD

Watch a video to learn more about the capabilities of the CTD sensor.

Specifications

Water Depth
Range: CTD-5 (0 to 5 m), CTD-10 (0 to 10 m).

Electrical Conductivity
Range: 0 to 120 dS/m (mS/cm). **Accuracy:** ±0.01 dS/m or ±10%. **Resolution:** 0.001 dS/m.

Temperature
Range: -40 to +50°C. **Accuracy:** ±1°C. **Resolution:** 0.1°C.

Data Logger Compatibility
Em50/Em50R/Em50G. Call for compatibility of Data Loggers.

Features

- Robust marine-grade epoxy overmold to resist corrosion in tough environments.
- Compact 3.4 cm diameter sensor body to fit into tight spaces.
- External logger with remote transmission option to deliver the data directly to your desktop.
- Permanent connection to collect data continuously without pulling up the sensor.

VACUUM SYSTEMS

Pore Water Sampler System

Pick the Vacuum System for Your Application. Then, pick the Pore Water Sampler that's right for you.

Applications:

- Quantify the presence of nutrients heavy metals, pesticides, and other contaminants.
- Measure net mineralization rates.
- Sample for organic carbon.

Don't take a soil core every time you want data. Leave your experimental site undisturbed and take more meaningful pore water samples with UMS's pore water samplers.

VS-Pro: Natural Sampling Suction

Precisely controlled tension means you sample what's actually in the soil water. Constant, unregulated tension preferentially samples the wet time periods, diluting your samples and giving inaccurate concentrations. UMS's unique tensiometer control matches sampler suction to the natural suction of the soil as conditions change, for the most accurate sample concentrations.

How does it work?

A pore water system is a quick access point for extracting soil water. Rather than digging up a chunk of soil and performing an extraction every time you want a sample, you install a specially tipped tube in the soil. Soil water samples are gently extracted from soil pores using suction pressure matched to natural soil water tension. Soil water tension is measured with a tensiometer; suction is set slightly above that tension to pull a sample.

VS/VS-Twin/VS-pro

Natural Sampling Suction

Power supply: 10.5 to 15 VDC. **Interface:** tensioLINK, RS485. **Memory:** 5000 readings. **Vacuum regulation range:** 0 to -85 kPa. **Dimensions:** 26 x 16 x 10 cm. **Enclosure:** Aluminum. **Operating temperature:** -10 to +45°C.

Additional Vacuums

VacuPorter Electric Pump

Max. vacuum: -85 kPa.
Max. pressure: 400 kPa.
Capacity: 10 liters/min.
Battery capacity: Internal rechargeable battery; 7 hours of operation.
Case: 30 x 25 x 13 cm.
Weight: 4.8 kg.
Operating temperature: -10 to +45°C.

VPS-2 Hand-Operated Floor Pump

Max. vacuum: -85 kPa.
Capacity: 0.41 liters per stroke.
Material: Aluminum and stainless steel, steel foot.
Height: 57 cm.
Weight: 2.2 kg.

Customized to Solute Type, UMS's patented silicone carbide tip is inert to a large range of compounds. Other tips are also available:

SIC20: Silicon Carbide

Widest range of compounds

Allows for sampling of a broad range of chemicals due to low sorption.

Shaft diameter: 20 mm; acrylic.
Shaft length: 20 to 210 cm; customized to order.
Porous ceramic: 20 mm diameter; 60 mm length.
Bubble point: -90 kPa.
Suction Tube: Polyethylene; 1.6 mm i.d.; 2.8 mm o.d.

SK20: Aluminum Oxide Ceramic

Suitable for determination of nitrate and common organic and inorganic substances.

Shaft diameter: 20 mm; acrylic.
Shaft length: 20 to 210 cm; customized to order.
Porous ceramic: 20 mm diameter; 60 mm length.
Bubble point: -100 kPa.
Suction tube: Polyethylene; 1.6 mm i.d.; 2.8 mm o.d.

SPE20: Polyethylene Nylon Membrane

Specially suitable for heavy metals, herbicides, and pesticides.

Shaft diameter: 20 mm; acrylic.
Shaft length: 20 to 210 cm; customized to order.
Porous ceramic: 20 mm diameter; 60 mm length.
Bubble point: -100 kPa; but the PE cover allows water flow only up to -20 kPa.
Suction tube: Polyethylene; 1.6 mm i.d.; 2.8 mm o.d.

Soil-Plant-Atmosphere Systems

Soil Moisture Sensors

Decagon's award-winning soil moisture sensors provide research-grade volumetric water content data at a price that lets you completely characterize your site.

Measure soils moisture, volumetric water content, temperature, dielectric permitivitty, and electrical conductivity with a wide variety of accurate sensors.

Find the right sensor for your needs. Read about the complete soil moisture sensor line on page 11.

Environmental Sensors

Decagon has a new line of canopy and atmospheric sensors, including the new Spectral Reflectance Sensors (measures NDVI and PRI) and the just-released sonic anemometer (measures wind speed and direction).

Sensors to measure solar radiation and PAR, soil temperature, precipitation amounts, and air temperature/relative humidity/vapor pressure are also available.

Other Envirionmental Instrumentation page 9.
DS-2 Sonic Anemometer page 8
Spectral Reflectance Sensor page 5.

Data Loggers

The Em50 line of data loggers offer quick access to your data. No programming needed. You can set up the logger, plug in your sensors, and start logging data in less than 30 minutes.

Read about these pre-programmed, weatherproof loggers that run on 5 AA batteries and can send data straight to your desk on page 35.

Data Management Software

DataTrac 3 graphs your data as it is gathered. Get near-real time reports, monitor battery life, transmission strength and sensor function, manage your wireless network, share data with colleagues, and more.

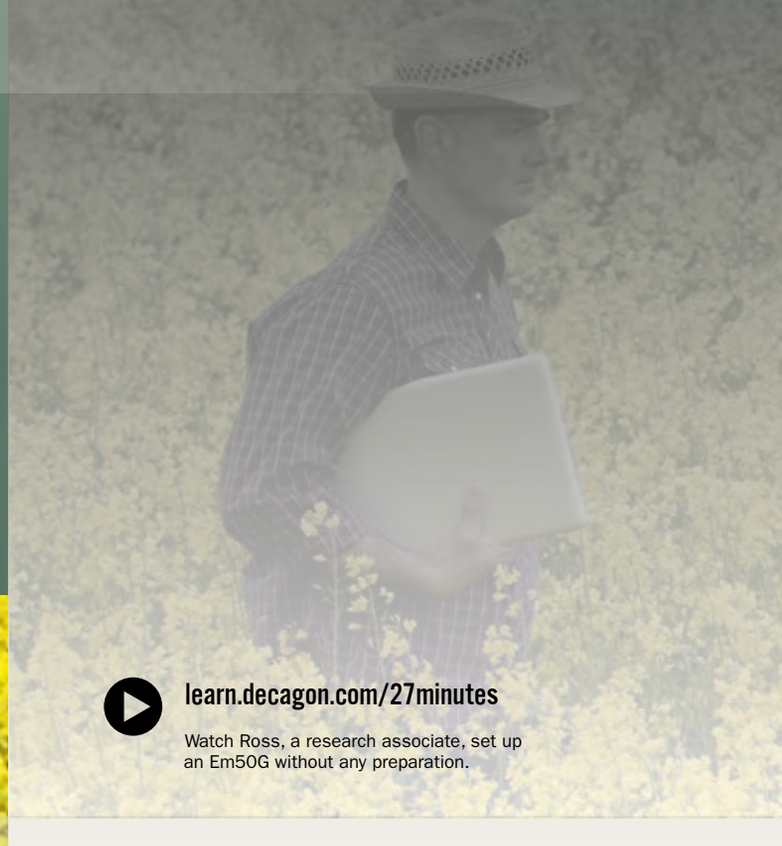
ECH20 Utility allows you to configure data and download data in a format ready for spreadsheet analysis.

Read about our basic and full featured versions on page 35.

Em50 Series

Data Loggers

Just plug in any Decagon sensor, set you sensor type and measurement intervals using drop down menus, and start logging data.



learn.decagon.com/27minutes

Watch Ross, a research associate, set up an Em50G without any preparation.

- **Pre-programmed**
  No user programming necessary.
- **Powered by 5 AA Batteries**
  No external power source required.
- **Weatherproof**
  No extra enclosure needed.

DataStation pairs with Em50R Logger (Right)

Em50

Applications

- Studies where data access is needed infrequently.
- Laboratory experiments.

Em50 Storage

Logger storage (36,000 scans), local DataTrac 3 storage with every download.

Em50R With DataStation

Applications

- Small-scale (less than 2 km^2) studies with a central data collection location.
- Studies that do not have cellular coverage.

Em50R Storage

Logger storage (36,000 scans), DataStation storage (1MB), local DataTrac 3 storage with every download from DataStation or Direct Connect.

Em50G

Applications

- Large and small-scale studies where daily access to data is advantageous.
- Studies with multiple researchers requiring access to the same data sets.

Em50G Storage

Automatic logger storage (36,000 scans), Decagon data server, local DataTrac 3 storage with every download.

Specifications

Data Logger: Universal Specifications. **Channels:** 5. **Interface:** Each channel can accept all digital, analog, or pulse Decagon sensors. **Storage:** >36,000 scans, each scan includes sensor name, date, time, and sensor measurements. **Scan interval:** User configured from 1 measurement/minute to 1 measurement/day (minimum Em50G scan interval every 5 minutes). **Power:** 5 AA batteries. **Enclosure rating:** IP55, NEMA3. **Data Plan:** Each Em50G comes with a one year cellular and server data plan.

DataTrac 3

Data Analysis Software

DataTrac 3 is a software program that collects and manages data from Em50 series data loggers. It allows you to monitor and manage transmitting loggers (Em50G, Em50R) and organize and graph data from all Em50 series loggers.

Organize data

DataTrac 3 automatically organizes both transmitted and manually collected data points and adds them to your files chronologically.

Organize and manage loggers

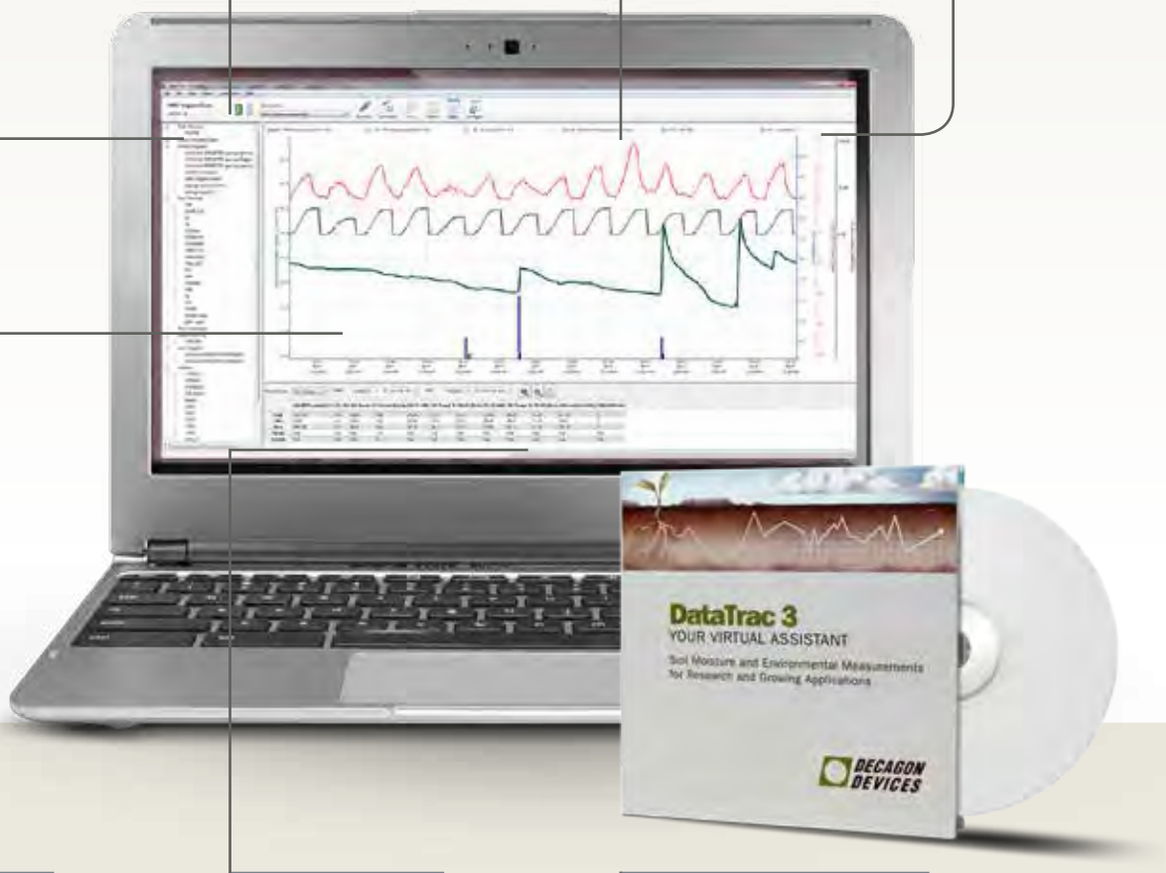
DataTrac 3 displays the status of all loggers in your network. Click on a logger to see all the data from the logger, monitor battery life, and check transmission strength.

Annotate your data

Adding comments and reminders as things happen can help you make sense of a growing-season's worth of data later.

See data in real time

DataTrac 3 downloads new data from wireless loggers automatically when it's running and every time it starts up.



Explore trends

Adjust date ranges, add or subtract data from specific sensors, change target bands to illustrate and explore your data.

Use built in models

Combined data streams and track useful calculated indicators like vapor pressure deficit, growing degree days, plant available water, pore water EC, and more.

Collaborate with colleagues

Subscribed colleagues can view and download data for analysis without any effect on the master data file.

ECH2O Utility

Interface with Data Loggers

ECH2O Utility is a free software program that allows you to connect to and interface with the Em50, Em50R, Em50G, Em5b data loggers as well as the ProCheck.

Battery Life

Monitor the battery life of data loggers in the field.

Download Data

Download collected data as a spreadsheet or a DataTrac 3 file.

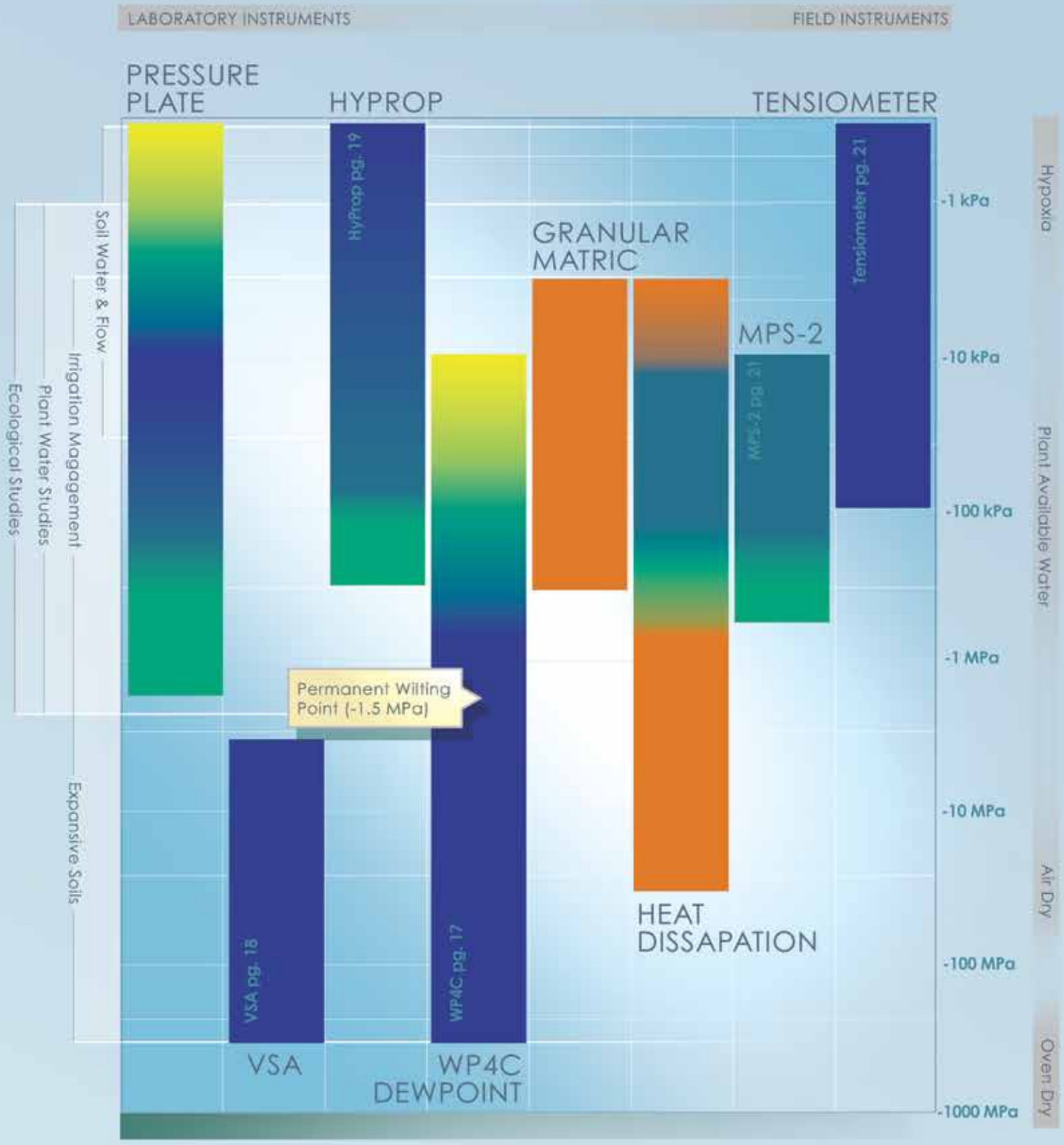
Calculator

Determine how many days of storage you have based on your preferred measurement interval.

Setup Screen

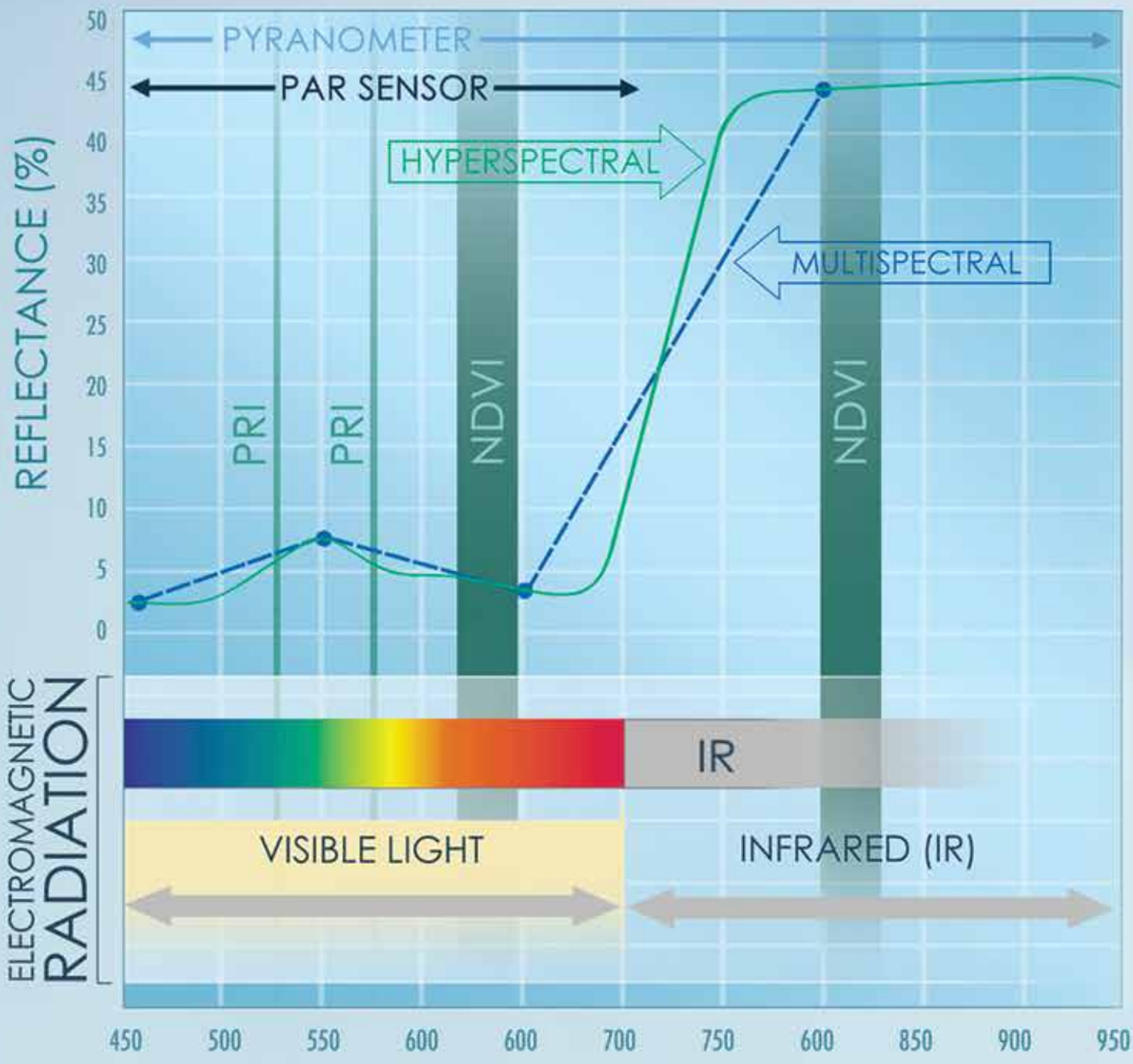
Set the date, time, and measurement intervals on a user-friendly setup screen, perform a telemetry test, and specify the sensor plugged in to each port.

WATER POTENTIAL INSTRUMENT RANGES



** Assumes equilibrium time 1-3 months*

SPECTRAL REFLECTANCE DATA



$$NDVI: \left(\frac{R800 - R630}{R800 + R630}\right)^* \qquad PRI: \left(\frac{R531 - R570}{R531 + R570}\right)^*$$

* R = % REFLECTANCE

Distributors

Canada - East
Hoskin Scientific Limited

4210 Morris Drive,
Burlington, ON L7L 5L6
tel: +1 905 333 5510
fax: +1 905 333 4976
email: salesb@Hoskin.ca
web: www.hoskin.ca

Canada-West
Hoskin Scientific Limited

3735 Myrtle Street
Burnaby, BC V5C 4E7
tel: +1 604 872 7894
fax: +1 604 872 0281
email: salesv@Hoskin.ca
web: www.hoskin.ca

Canada-Quebec
Hoskin Scientifique Limited

4210 Morris Drive,
Burlington, ON L7L 5L6
tel: +1 905 333 5510
fax: +1 905 333 4976
email: salesb@Hoskin.ca
web: www.hoskin.ca

United States of America
Decagon Devices, Inc.

2365 NE Hopkins Court
Pullman WA, 99163
tel: +1 509 332-2756
fax: +1 509 332-5158
email: sales@decagon.com
web: www.decagon.com

Mexico
Ruber Eim De México

Av. Arcos Ote 195-B
Col. Jardines del Sur
CP 16050, Xochimilco, Mexico D.F.
tel: +52 55 5653 3077
fax: +52 55 5675 2627
email: rubereim@prodigy.net.mx
web: www.rubereimdemexico.com

Costa Rica
Lapaca

Casa H-13, las Sierras de La Unión
De San Rafael de La Unión
Cartago
tel/fax: +506 2279 7062
cell: +506 8891 9895
email: alarias@racsa.co.cr
web: www.lapacacr.com

Colombia
Coltein Ltda.

CR 27 53 11 OF302
Bogotá D.C.
tel: +571 347 2038
fax: +571 349 2088
email: info@coltein.com
web: www.coltein.com

Peru
MorpH2O L.A.

tel/fax :+56 2 821 6095
cell: +56 9 7 135 8362
email: contacto@morph2ola.com
web: www.morph2ola.com

Brazil
Decagon Devices LatAm Ltda.

R. José Alves dos Santos, 281 - Sala 102
São José dos Campos – São Paulo - 12230-081
tel: +55 12 3307 1003
email: contato@decagon.com.br
web: www.decagon.com.br

Argentina
Instrumentos del Sur S.A.

Gaspar Campos 1175
(1638) Vicente Lopez
Pcia. de Buenos Aires
tel./fax: +54 11 4791 0169
cell: +54 9 11 54088397/
1154088397
email: info@idelsur.com
web: www.idelsur.com

Chile
MorpH2O L.A.

Longitudinal Sur #215
Casilla 284
Buin
tel/fax: +56 2 821 6095
cell: +56 9 7 135 8362
email: contacto@morph2ola.com
web: www.morph2ola.com

United Kingdom
Labcell LTD.

Unit 3a, Mansfield Park
Four Marks, Alton
Hants. GU34 5PZ
tel: +44 01420 568 150
fax: +44 01420 568 151
email: mail@labcell.com
web: www.labcell.com

Spain
Lab-Ferrer

c/Ferran Catòlic,
3. 25.200 Cervera (Lleida)
tel/fax: +34 973 532110
email: info@lab-ferrer.com
web: www.lab-ferrer.com

Portugal
Lab-Ferrer

c/Ferran Catòlic,
3. 25.200 Cervera (Lleida)
tel/fax: +34 973 532110
email: info@lab-ferrer.com
web: www.lab-ferrer.com

Sweden
Toragon AB

Umestan Företagspark
S-903 47 Umeå
tel: +46 90 100 260
fax: +46 90 100 261
email: info@toragon.se
web: www.toragon.se

EUROPE

France
Sols Mesures

17, rue Jean Monnet
Z.A. des Côtes
78990 Elancourt
tel: +33 1 30 503 450
fax: +33 1 30 503 449
email: info@sols-mesures.com
web: www.sols-mesures.com

Germany/Austria
UMS GmbH München

Gmunder Str. 37,
D-81379 München
tel: +49 89 1266 52 14
fax: +49 89 12 66 52 20
email: ums@ums-muc.de
web: www.ums-muc.de

Netherlands/Benelux
CaTeC b.v.

Turfschipper 114
2292 JB Wateringen
The Netherlands
tel: +31 174 272330
fax: +31 174 272340
email: info@catec.nl
web: www.catec.nl

Poland
Geomor-Technik Sp. z o.o.

ul. Modra 30,
PL 71-220 Szczecin
tel: +48 91 482 00 90
tel/fax: +48 91 482 60 87
email: geomor@geomor.com.pl
web: www.geomor.com.pl

Greece
Scientact SA

16 Kanari St
54644 Thessaloniki
tel: +30 2310 946 126
fax: +30 2310 947 005
email: info@scientact.com.gr
web: www.scientact.com.gr

Italy
Misure snc

Via degli Olmetti
38 00060 Formello (Roma)
tel: +39 069075535
fax: +39 069075536
email: info@misure.net
web: www.misure.net

Denmark
Inverva ApS

Daruplund 29, 1, th
DK-2660 Brondby Strand
tel: +45 6595 9454
fax:+45 6595 9452
email: info@inverva.com
web: www.inverva.com

Romania
S. C. Terra Preta SRL

Bd. Unirii, Nr. 61, Bl. F3, Sc. 4, Ap. 510
Sector 3, Bucuresti
cod 030828
tel: +40 021 326 8567
fax: +40 031 101 6676
email: office@terra-preta.ro
web: www.terra-preta.ro

Turkey
Bilmar

Tunali Hilmi Caddesi,
Büklüm Sokak
No: 63/57
06700 G.O.P. Ankara
tel: +90 0312-468 28 35
fax: +90 0312-468 17 17
email: bilkim@bilmar.com.tr
web: www.bilmar.com.tr

MIDDLE EAST

Israel
Meteo-Tech

31 Lehi Street
Bnei Brak, 51200
tel: +972-3-6160598
fax: +972-3-6184384
email: info@meteo-tech.co.il
web: www.meteo-tech.co.il

Middle East / MENA region
ICT International

1100 Salt
19110 Jordan
tel: +962 7770 54400
fax: +962 7976 54400
email: ghazi@ictinternational.com.au
web: www.ictinternational.com.au

Morocco
Metagrhyd

Rue Pasquier, Résidence Abdelmoumen,
Immeuble 6, N°12, Franceville II,
20390 Casablanca
tel.: +212 522 254 900
fax: +212 522 254 903
email: metagrhyd@gmail.com
web: www.metagrhyd.com

South Africa
CS Africa

1a Meson Street
Technopark
Stellenbosch
tel: +27 21 880 9960
fax: +27 21 880 0240
email: sales@campbellsci.co.za
web: www.campbellsci.co.za

Czech/Slovak Republics
Ekotechnika Spol. S.R.O.

Mokropeska 1832
252 28 Cernosice
tel: +420 737 044 323
fax: +420 251 640 512
email: ekotechnika@ekotechnika.cz
web: www.ekotechnika.cz

Russia
Lab Depot Corporation

7F, Torfyanaya doroga
Business center "Gulliver-2"
Office 318
St. Petersburg - 197374
tel: +7 812 320 60 48
fax: +7 812 320 60 48
email: es@labdepot.ru
web: www.labdepot.ru

ASIA

China
Ecotek

Unit A,22F., Chengming Building
No.2 Xizhimen Nadajie
Beijing
tel: +86 10 51665551,66001653
fax: +86 10 66001652
email: info@ecotek.com.cn
web: www.ecotek.com.cn

India
P.S.P Soilsearch Equipment (P) Ltd.

62/J/1, Maharaja Tagore Road,
Kolkata - 700031
tel: +91 33 24732151
fax: +91 33 24733215
email: soilsearch_equipment@vsnl.net
web: www.pspsoilsearch.com

Malaysia
Team Medical & Scientific Sdn Bhd

No. 41, Jalan Anggerik
Vanilla T-31/T
Kota Kemuning
40460 Shah Alam
Selangor
tel: +60 3 5122 5108
fax: +60 3 5122 1608
email: info@tms-lab.com
web: www.tms-lab.com

Thailand
Win Siam Co., Ltd.

701/12 Wong-Sawang Road
Bang Sue, Bangkok 10800
tel. +66 2910 9898
email: winsiam@gmail.com
web: www.winsiam.com

Indonesia
ICT International Pty. Ltd.

tel: +61 267 726770
fax: +61 267 727616
email: asiasales@ictinternational.com.au
web: www.ictinternational.com.au

Bulgaria
Scientact BG Ltd.

46, Prof. Kiril Popov Str.
Studentski Grad
1734 Sofia
tel : +359 24684867
email: bg@scientact.com
web: www.scientact.com

Korea
C & H

Room #1505 Hwanghwa Bldg.
Yeoksam-dong, Kangnam-ku
Seoul
tel: +82 2 501 3869
fax: +82 2 556 0480
email: info@candh.co.kr
web: www.candh.net

Japan
Ainex Co., Ltd.

2-16-1, Minamikamata, Ota-ku
Tokyo - 144-0035
tel: +81 3 5713 0388
fax: +81 3 5713 1388
email: info@ai-nex.co.jp
web: www.ai-nex.co.jp

Taiwan
Wilson Scientific Co. Ltd.

9F-3, No. 159 Sec.1
Shin-Tai-Wu Rd.
Shijr, Taipei County
tel: +886 2 2690 7696
fax: +886 2 2690 7721
email: wilsonn@tpts5.seed.net.tw
web: www.wilsonsci.com.tw

Philippines
ICT International Pty. Ltd.

tel: +61 267 726770
fax: +61 267 727616
email: sales@ictinternational.com.au
web: www.ictinternational.com.au

AUSTRALIA

Australia/New Zealand
ICT International Pty. Ltd.

PO Box 503
Armidale. NSW 2350
tel: +61 267 726770
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